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USER'S MANUAL

SYNCHRONOUS SIGNAL GENERATOR (-4 OPTION) SD375 DYNAMIC ANALYZER II

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Spectral Dynamics Division
United States: P.O. Box 23575 • San Diego, CA 92123-0575 • (619) 268-7100 • TWX 910-335-2022

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Spectral Dynamics Division

United States: P.O. Box 23575 • San Diego, CA 92123-0575 • (619) 268-7100 • TWX 910-335-2022
Europe: Horton Manor • Stanwell Road • Horton, Slough, SL3 9PA, England • Telephone: Colnbrook 3211 • Telex: 849406

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SECTION I

GENERAL INFORMATION

1.1 INTRODUCTION

This manual contains operating instructions and initial checkout procedures for the Synchronous Signal Generator (SSG) Option for the Scientific-Atlanta Model SD375 Dynamic Analyzer II. The manual is divided into three sections. Each section covers a specific aspect of the option. This manual is written for the operator and contains no maintenance information. Maintenance information for this option is included in the SD375 Service Manual.

1.2 EQUIPMENT DESCRIPTION

The SSG Option circuitry is contained on PWA 21876500. This PWA is located in card position A5A17 in the SD375. In addition to circuit card A5A17, the SSG Option requires that the Translator (-1 Option) be installed (PWA's 21180600, 21284500, card positions A5A4 and A5A5).

The SD375 SSG Option is a convenient source of broad band white noise, band limited pseudo-random noise, and single sine wave analog outputs for the excitation of external systems or networks for performance evaluation. The SSG Option output modes (BAND LIMITED, BROAD BAND, and SINGLE FREQ) and output levels (0.05 V to 5 V in a 1, 2, 5 sequence) are established from a program (PRGM) menu. (The menu, titled SIGNAL SOURCE, becomes available with the SSG Option installed.)

1.3 SPECIFICATIONS

Signal Characteristics

BAND LIMITED — 400 constant-amplitude random-phased tonals equally spaced at Δf intervals and centered within each cell (or FFT bin). Signal output level is selectable from 0.05 vrms to 5 vrms in a 1, 2, 5 sequence. Sequence length of the noise matches the selected input memory period.
Range capability: near dc to 40 kHz.
Flatness: ± 3 dB to 40 kHz.

BROAD BAND — Unfiltered white noise from near dc to 100 kHz in selectable levels from 0.05 vrms to 5 vrms in a 1, 2, 5 sequence.
Flatness: ± 3 dB to 50 kHz, $+3$ dB to -6 dB in 100 kHz.

SINGLE FREQ — Frequency of the signal output is determined by the CURSOR group ADRS control and the selected full scale analysis range. Selectable resolution determined by the Δf filter spacing.
Range capability: 0.0025 Hz to 20 kHz.
Flatness: ± 3 dB to 20 kHz.
Spurious noise: In band harmonic and spurious noise components less than -40 dB from full scale output.

ZOOM Limited — Not on the SIGNAL SOURCE menu; selected by turning the Translator ON in the BAND LIMITED mode. Output noise is now concentrated within the selected ZOOM window.

Sync Pulse (Frame Sync)

An output pulse, 1 μs in duration, with an amplitude of 5 V (nominal) is provided at rear-panel BNC connector, J16. This pulse flags the start of each noise sequence in the BAND LIMITED and ZOOM Limited modes. TTL type output.

Out-of-Band Signal

The rms value of the out-of-band signal is at least 9 dB down from the total rms value of the generated in-band signal.

Output Impedance

50 Ω (Nominal)

SECTION II

INSTALLATION

2.1 INTRODUCTION

This section contains instructions for field installation of the SD375 SSG Option. Procedures for inspecting, checking for physical damage, reshipment and returning under warranty or damage claims are in the SD375 User's Manual.

2.2 PREPARATION FOR USE

2.2.1 Option Included with the Instrument

If you have received the SD375 with the option already installed, you won't need to read this. Proceed to Section III, Operation.

2.2.2 Option Field Installation

Read these instructions first, before attempting installation of the SSG Option circuit card.

a. Make sure the SD375 is operating properly (including the Translator Option).

b. Remove power from the SD375 (turn it off).

c. Unplug the instrument.

d. Remove the top cover.

CAUTION

After you have removed the top cover from the SD375, you will notice that the power supply and crt assemblies have safety plates installed. These safety plates need not be removed for installation of this option. Voltages are present inside the instrument even with the power cord disconnected. Be careful!

e. Make sure that all plug-in IC's are firmly seated and that component parts mounted on the SSG Option circuit card do not protrude enough to cause damage when the circuit card is inserted.

f. Carefully insert the SSG Option circuit card in the slot marked A17. Make sure that the components on the A17 card are pointed in the same direction as the rest of the circuit cards.

g. Make sure the card is fully seated and the top of the card is even with the other cards.

h. Replace the top cover of the SD375.

i. Plug in the power cord, turn the instrument back on and proceed to Section III.

SECTION III

OPERATION

3.1 INTRODUCTION

This section provides the operator with a description of the operating modes, the front-panel touch controls and indicators that affect or are affected by the option, and an operational checkout of the option.

3.2 GENERAL OVERVIEW

The primary purpose of a dynamic analyzer is to determine what a "specimen" does to an input signal in order to get an output signal. The input signal may be an "impact", the output the resultant vibration. The characteristic of the specimen that produced the output signal is the specimen's "transfer function". If the transfer function can be accurately measured, the output can be calculated for any given input.

During transfer function measurement of either electronic or mechanical systems, there is a requirement to "excite" the specimen under test with a known input. Typically, this input is generated by a separate signal generator that can generate "white noise" digitally over some frequency range. The self-contained SSG Option not only provides the necessary white noise excitation, but also a band limited signal and a single frequency sine wave output are included, thus reducing the number of instruments required for field measurements.

3.3 OPERATION

Before you get started, there are certain operating conditions you should be aware of. These conditions are as follows:

To utilize the full capability of the SSG Option, the Translator (-1 Option) circuit boards must be installed. The translator does not have to be turned on for the SSG Option to operate, but it must be present. Without the Translator Option, only one SSG Option menu item can be selected, the Broadband (white noise) signal. The other two signals (Band Limited and Single Frequency) utilize selected portions of the Translator Option circuitry. This leads to an operating condition concerning the Single Frequency signal.

While it is possible to place the Single Frequency signal at any cell (or FFT bin) location (from 1 to 399) on any analysis range (except the 50 kHz and 100 kHz analysis ranges), the number of cells (or FFT bins) available is dependent upon the Translator ZOOM setting, even if the Translator is *not* turned on. An explanation of this operating condition and table of cell locations versus zoom settings is provided with the instructions for the Single Frequency mode.

Both the Band Limited and Single Frequency modes will *not* operate in either the 50 kHz or the 100 kHz analysis ranges. The 40 kHz analysis range can be used, without any problems, if it is selected in ascending order. For example, if either the 50 kHz or the 100 kHz analysis ranges are selected, you will have to step the selection back to the 20 kHz analysis range, and then return to the 40 kHz range.

The SSG Option signal OUTPUT is BNC connector J17 located on the rear panel of the SD375. With the SSG Option installed, and the SD375 turned on, one of three signals from the option will always be present at J17.

Output level selection for all three signals is accomplished by using the CH A, VOLTS UP/DOWN touch controls *only* when the SIGNAL SOURCE menu is being displayed.

3.3.1 Getting Started

With the SSG Option installed, there is a new menu available to the operator, specifically for signal selection. Figure 3-1 tells how to access the menu, provides a menu example and operating instructions for signal and output level selection.

The signal examples shown in the following descriptions were accomplished by connecting a BNC cable from J17 on the rear panel of the SD375 to the INPUT A BNC connector on the front panel of the SD375.

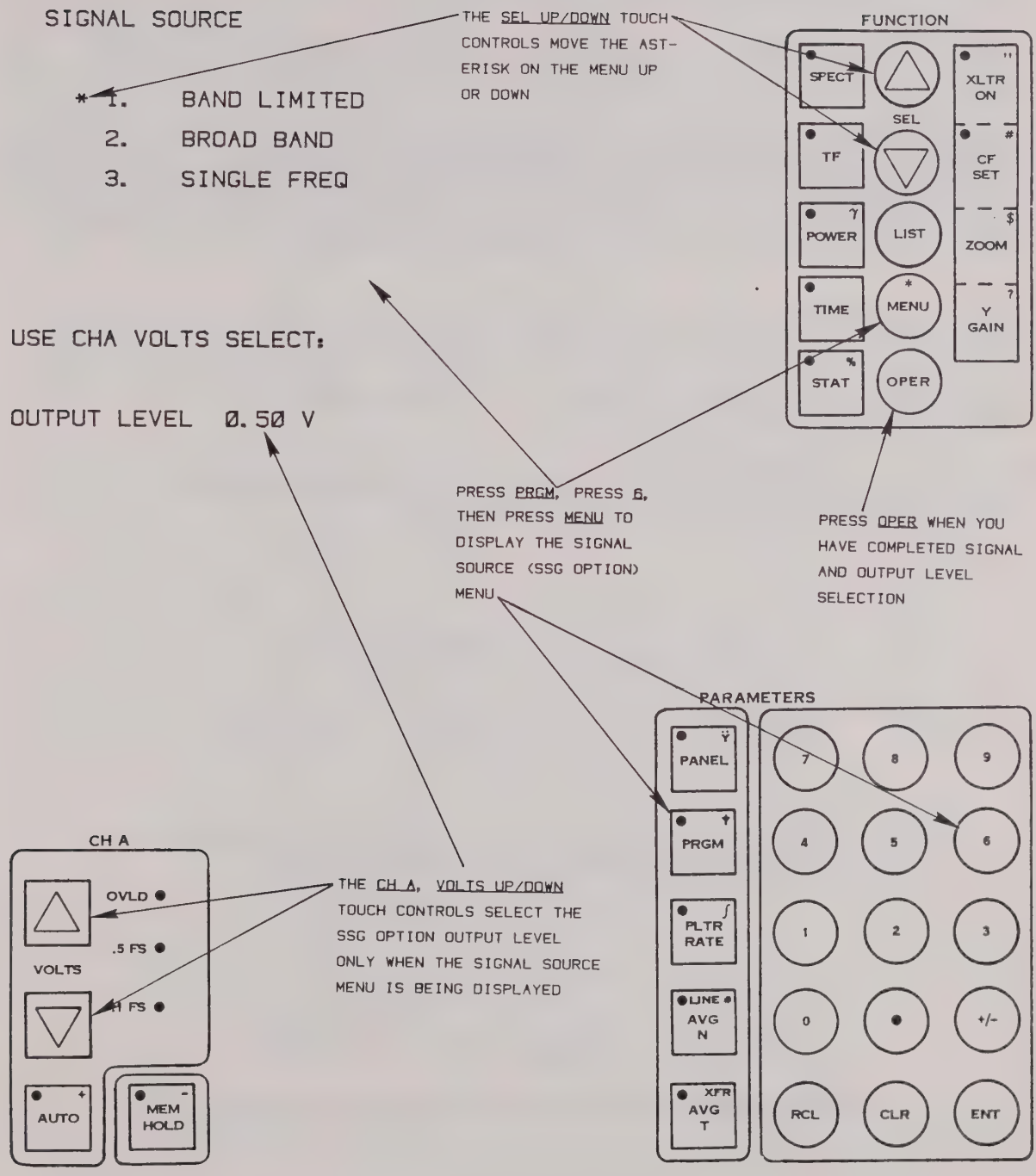


Figure 3-1. Signal Source Menu Operation

3.3.2 A Description of the SSG Option Menu Items

* 1. BAND LIMITED (AND ZOOM LIMITED)

The frequency content of this synchronous noise output is limited, by internal low pass filtering, to the first nineteen analysis ranges on the SD375. The clock rate of the random sequence is slaved to the input A/D sampling rate, hence the name Synchronous Signal Generator (SSG). The synchronous noise output contains 400 tonals space at Δf intervals and *centered* within each filter (or FFT bin). Each tonal contains a full number of complete cycles within the selected memory period.

This controlled generation of full period tonals permits the use of the rectangular weighting function for analysis of system input/output characteristics without degradation caused by truncation conditions. The significant result is a narrower effective filter shape which means sharper resonances can be measured and the signal-to-noise ratio improved. Up to 15 dB of increased transfer function dynamic range can be obtained using SSG excitation.

Figure 3-2 is an example of a BAND LIMITED signal with rectangular weighting applied. Note the flat response even though the display is in the Real Time (RT) mode.

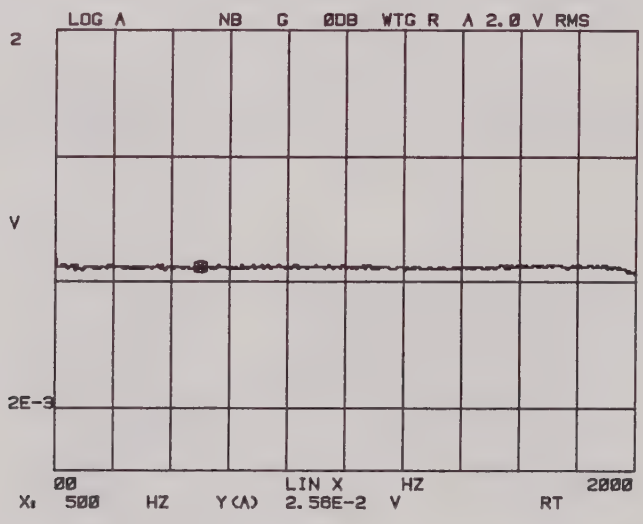


Figure 3-2. BAND LIMITED Signal with Rectangular Weighting

Figure 3-3 consists of two dual displays taken from the "Zoom Limited Check" portion of the Operational Checkout procedures in this section. The display mode is selection 8, SPECT A & ZOOM A, from the SPECTRUM MENU. Both the upper and lower traces are displays of the same channel, giving a comparison of the same data, both translated (lower trace) and narrowband or non-translated (upper trace). Note that as the zoom factor is increased (in this case, from Z2 to Z5), the upper trace signal narrows. This is because, with the Translator Option turned on, the SSG excitation output is concentrated within the zoom window. This is equivalent to bandpass filtering the noise excitation except the synchronous clocking of the noise output is maintained and the frequencies are now spaced at the selected zoom window filter spacing. This concentration of energy allows higher forcing functions in the frequency range of interest which improves signal-to-noise enhancement.

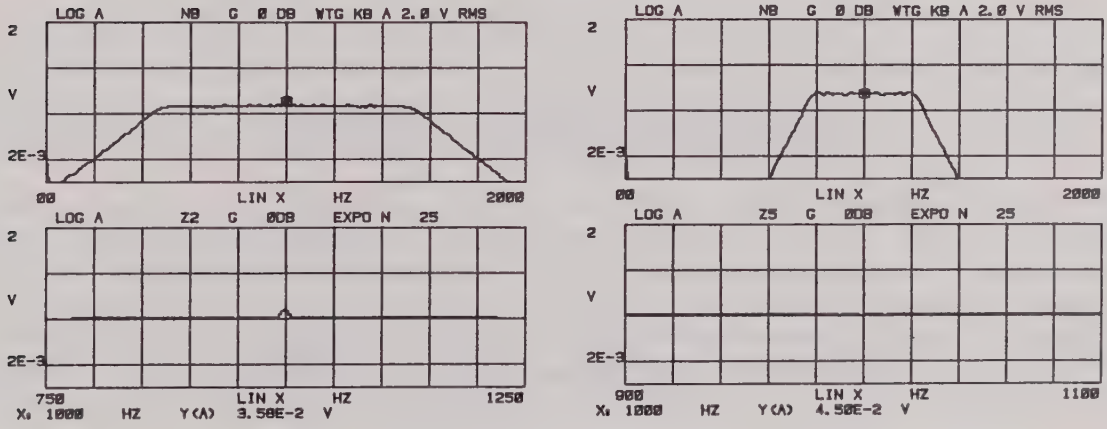

LOG A NB G 0 DB WTG KB A 2.0 V RMS
2
V
2E-3
00
LIN X HZ
2000
LOG A Z2 G 0DB EXPO N 25
750
1250
X: 1000 HZ Y(A) 3.58E-2 V
LOG A NB G 0 DB WTG KB A 2.0 V RMS
LOG A Z5 G 0DB EXPO N 25
900
1100
X: 1000 HZ Y(A) 4.50E-2 V

Figure 3-3. Dual Displays of the same BAND LIMITED signal in the Zoom Limited Mode. The display on the left has a Zoom of 2, the display on the right, a Zoom of 5

* 2. BROAD BAND

This is the "white noise" output with a bandwidth of 100 kHz regardless of the selected analysis range. The output level for this signal is controllable through the CH, A, VOLTS UP/DOWN front-panel touch controls *only* when the SIGNAL SOURCE menu is being displayed. This is the only SSG Option mode that does not require the Translator Option to be present. Figure 3-4 is an example of the BROAD BAND signal.

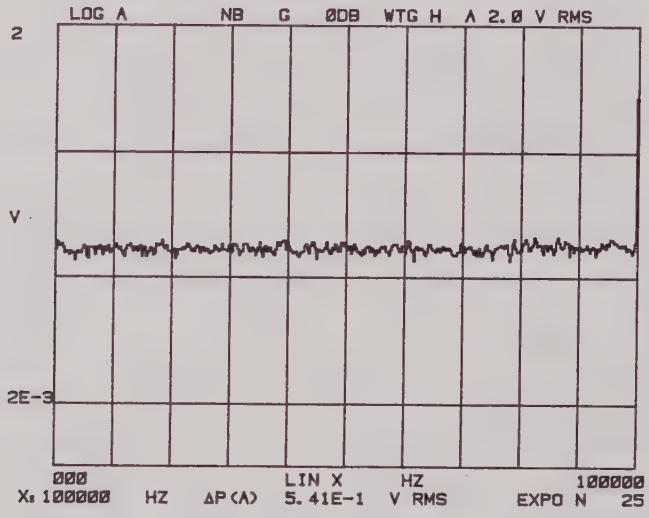


Figure 3-4. Averaged BROAD BAND Signal, 100 kHz Analysis Range.

* 3. SINGLE FREQ

This signal is a single sine wave analog output. The frequency of this signal is determined by the CURSOR group ADRS touch control and the selected analysis range. The signal is centered at the selected ADRS location (cell or FFT bin) allowing the weighting function to be switched out resulting in a narrower effective filter shape.

To use the SINGLE FREQ mode, proceed as follows: First, select SINGLE FREQ (selection 3) on the SIGNAL SOURCE menu. While the menu is still being displayed, select the desired output level using the CH A, VOLTS UP/DOWN touch controls. Press OPER. Select the desired analysis range (up to 40 kHz). Press the CURSOR group ADRS touch control. On the PARAMETERS group numbered "keypad",

select the desired ADRS location (a number from 1 to 399), then press ENT. The signal will appear at the selected location. Once this is accomplished, the cursor can be moved in either direction, without affecting the signal. To change the signal, another ADRS entry has to be made.

To convert a specific frequency to a cell location, the following formula is provided:

$$\frac{400 \times \text{Desired Frequency}}{\text{Full Scale Analysis Range}} = \text{Cell Location}$$

For example, if you want to generate a 315 Hz tonal, then:

$$\frac{400 \times 315}{1000} = 126$$

The ADRS entry will be cell 126 (with the 1 kHz analysis range selected). Occasionally you will encounter a value that is not a whole number. Since only whole number values are valid for ADRS entry, it is best to select the lowest full scale analysis range closest to (but greater than) the desired single frequency.

An alternate method of Single Frequency placement can be accomplished by using the Translator. This is how you do It: Turn the Translator on, but do not set the center frequency (CF SET). Press the CURSOR LEFT/RIGHT control in the direction of the desired frequency. Observe the cursor x-axis readings on the display. When you reach the frequency you want, turn the Translator off. A tonal will appear at the cursor location (you don't need to use the ADRS, #, ENT sequence when you use this method). If you want to know the cell location of the tonal, press ADRS, then RCL (make sure the cursor is on the peak of the tonal). The cell number will appear in the upper right hand corner of the display.

As stated previously in this section, the number of cell locations available is dependent upon the Translator ZOOM setting, even with the Translator turned off. A ZOOM factor of 100 will give you the maximum amount of ADRS (cells or FFT bins) locations (from 1 to 399) to work with. If you're not sure as to the current Translator ZOOM setting, turn the Translator on and note the annotation change across the top of the grid on the display. The indication for the current ZOOM setting will appear as Z2, Z5, Z10, Z20, Z50 ro Z100. Table 3-1 provides a list of the ZOOM settings and the maximum number of cells that can be utilized for each setting. Usually, it is best to select a ZOOM of 100 so as not to limit the number of cell locations available.

TABLE 3-1

ZOOM SETTING	CELL LOCATIONS	
	MIN	MAX
Z2	50	350
Z5	20	380
Z10	10	390
Z20	5	395
Z50	2	398
Z100	1	399

Figure 3-5 is an example of a SINGLE FREQ tonal placed at cell (or FFT bin) 100 with an output level of 1 vrms. This example was taken from the operational checkout procedures located at the end of this section.

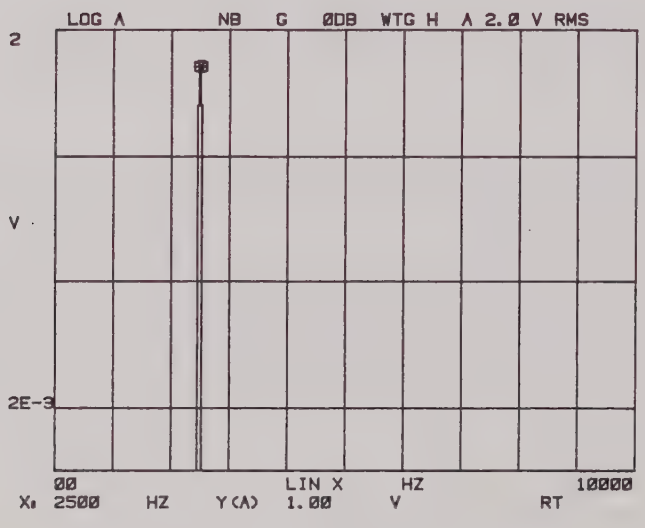


Figure 3-5. SINGLE FREQ Tonal, ADRS 100, 1 vrms.

OUTPUT LEVEL

The output of the SSG Option is selectable in a 1, 2, 5 sequence as shown in Figure 3-6. Level selection is accomplished by using the front-panel CH A VOLTS, UP/DOWN touch controls *only* when the SIGNAL SOURCE menu is being displayed.

```
USE CHA VOLTS SELECT:

OUTPUT LEVEL  Ø.Ø5 V, Ø.1Ø V, Ø.2Ø V,
              Ø.5Ø V, 1.Ø V, 2.Ø V, &
              5.Ø V
```

Figure 3-6. SIGNAL SOURCE Menu Output Level Selections.

SYNC OUTPUT

A TTL trigger output coincident with the start of each random sequence is provided on rear-panel BNC connector J16. Each sequence length matches the memory period of the analyzer. This SYNC output can be used as the SYNC TIME trigger input for SYNC TIME averaging functions.

3.4 OPERATIONAL CHECKOUT PROCEDURES

The display examples in this checkout procedure are provided for comparison purposes only. It is not intended that the data display on your instrument will be exactly the same as the examples in the checkout procedures. However, if the checkout procedures are followed correctly, the annotation will be the same and the differences between the signals you see on your instrument and those shown in this checkout procedure will be negligible.

NOTE

The checkout procedures specify, at a certain step, selection of Kaiser-Bessel weighting. Some instruments will have Flat Top weighting instead of Kaiser-Bessel. In these cases Flat Top weighting should be selected.

3.4.1 SINGLE FREQ CHECK

a. Make sure that both the SSG Option circuit card (A17) and the Translator Option circuit cards (A4 and A5) are properly installed.

b. Connect a BNC cable between J17 on the rear panel of the SD375 and the INPUT A BNC connector on the front panel.

c. Press the following touch controls in the indicated sequence:

PARAMETERS Group
1. Press PANEL
2. Press O
3. Press RCL

DISPLAY Group
1. Press UPPER (you should have a single trace display of CH A.)

PARAMETERS Group
1. Press PRGM
2. Press 6

FUNCTION Group
1. Press MENU. The following menu will be displayed:

```
SIGNAL SOURCE

* 1.   BAND LIMITED
  2.   BROAD BAND
  3.   SINGLE FREQ


USE CHA VOLTS SELECT:

OUTPUT LEVEL  Ø.5Ø V
```

Using the FUNCTION group SEL UP/DOWN touch controls, select SINGLE FREQ. Using the CH A VOLTS, UP/DOWN touch controls, select an OUTPUT LEVEL OF 1.0 V (remember, you have to be displaying the SIGNAL SOURCE menu to do this).

FUNCTION Group
1. Press OPER

Using the CH A VOLTS, UP/DOWN touch controls, select an input level of 2.0 vrms. Make sure the 10 kHz frequency range is selected.

CURSOR Group Y Units
1. Press V

CURSOR Group
1. Press ADRS

PARAMETERS Group
1. Press 40
2. Press ENT

Compare the display with Figure 3-7 and note that the tonal is located at 1000 Hz and has an amplitude of 1 vrms, ± 25 mv.

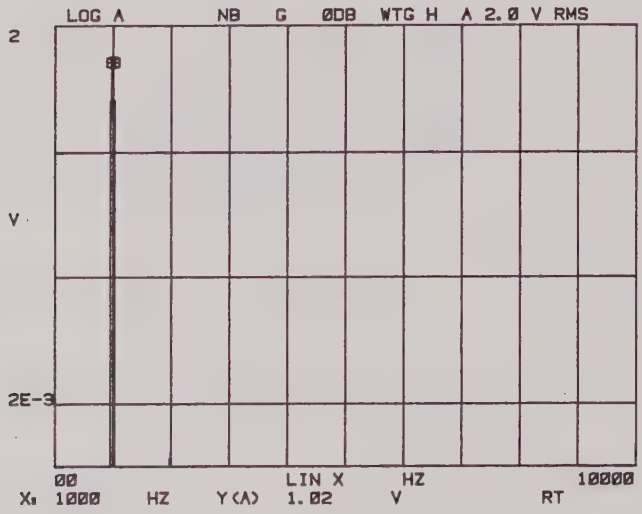


Figure 3-7. SINGLE FREQ Tonal, ADRS 40, 1 vrms.

CURSOR Group
1. Press ADRS

PARAMETERS Group
1. Press 100
2. Press ENT

Compare the display with Figure 3-8 and note that the tonal is now located at 2500 Hz and has an amplitude of 1 vrms, ± 25 mv.

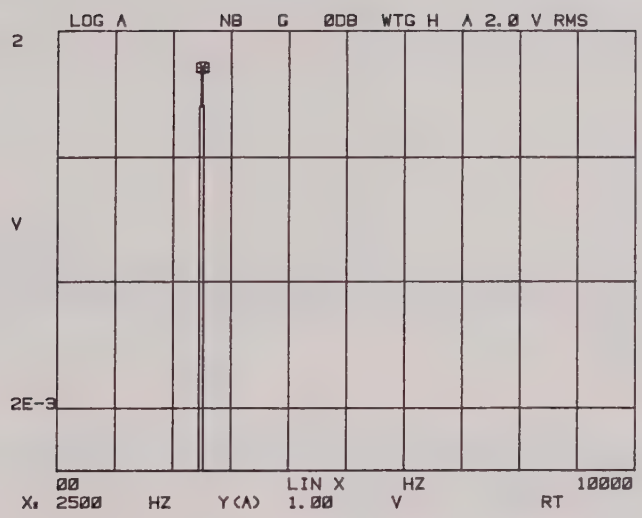


Figure 3-8. SINGLE FREQ Tonal, ADRS 100, 1 vrms.

3.4.2 BAND LIMITED CHECK

a. Press the following touch controls in the indicated sequence:

PARAMETERS Group
1. Press PRGM
2. Press 6

FUNCTION Group
1. Press MENU

Using the FUNCTION group SEL UP/DOWN touch controls, select BAND LIMITED. Using the CH A VOLTS, UP/DOWN touch controls, select an OUTPUT LEVEL OF 0.50 V.

FUNCTION Group
1. Press OPER

Using the CH A & B Group FREQ UP/DOWN touch controls, select the 2kHz frequency range. Make sure the 2 V input level is still selected.

CH A & B Group
1. Press RECT

Compare the display with Figure 3-9 and note the flat response when rectangular weighting is selected.

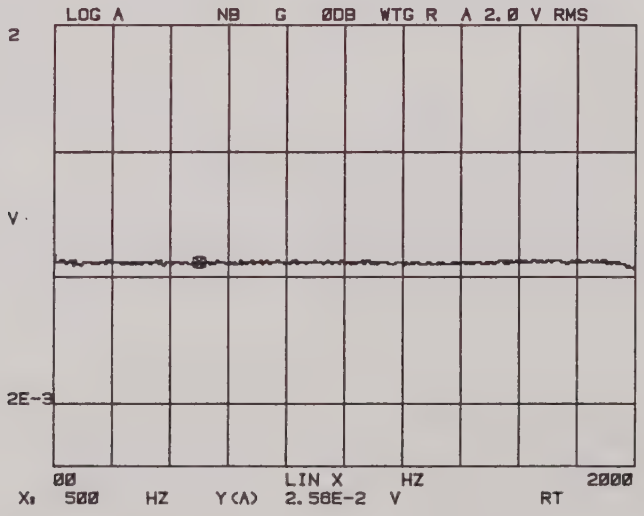


Figure 3-9. BAND LIMITED Signal With Rectangular Weighting.

CURSOR Group
1. Press ADRS

PARAMETERS Group
1. Press 400, ENT

CURSOR Group
1. Press ΔP

DISPLAY Group
1. Press M1

PARAMETERS Group
1. Press AVG N, 10, ENT

AVERAGE (M1) Group
1. Press EXPO, ERASE, START

Compare the display with Figure 3-10 and note the overall amplitude reads 5.00E-1 V RMS, ± 25 mv.

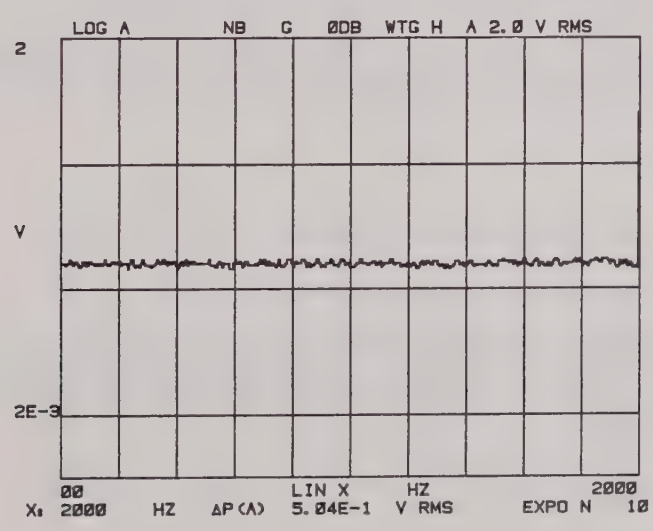


Figure 3-10. Averaged BAND LIMITED Signal in the ΔP Mode.

3.4.3 ZOOM LIMITED CHECK

a. The following checks have you displaying the BAND LIMITED signal with each Translator ZOOM setting (Z2, Z5, Z10, Z20, Z50, Z100). Each time a ZOOM setting is changed, you have to press the AVERAGE (M1) group ERASE and then START touch controls, and then compare the display with the appropriate figure *after* averaging is completed.

DISPLAY Group
1. Press RT

AVERAGE (M1) Group
1. Press ERASE

CH A & B Group
1. Press KB (or FLAT TOP)

CURSOR Group
1. Press NORM

FUNCTION Group
1. Press SPECT, MENU

Using the FUNCTION group SEL UP/DOWN touch controls, select SPECT A & ZOOM A (Menu selection 8) on the SPECTRUM MENU.

FUNCTION Group
1. Press OPER

DISPLAY Group
1. Press DUAL

Using the CURSOR group LEFT/RIGHT touch controls, move the cursor to the center of the display (1000 Hz reading on the x-axis). Using the FUNCTION group ZOOM touch control, select ZOOM 2 (Z2).

DISPLAY Group
1. Press M1

PARAMETERS Group
1. Press AVG N, 25, ENT

AVERAGE (M1) Group
1. Press EXPO, ERASE, START

Compare the display with Figure 3-11.

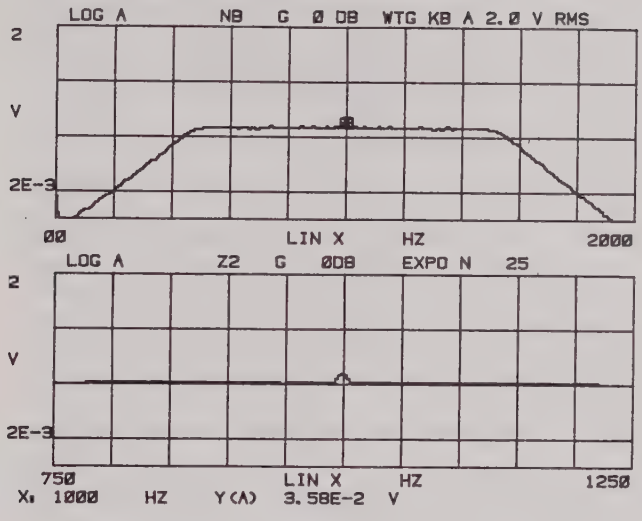


Figure 3-11. Dual Display of the BAND LIMITED Signal with the Lower Trace Showing Translated Data with a ZOOM of 2.

Press the AVERAGE (M1) group ERASE touch control, select ZOOM 5, press the AVERAGE (M1) group START touch control and compare the display with Figure 3-12.

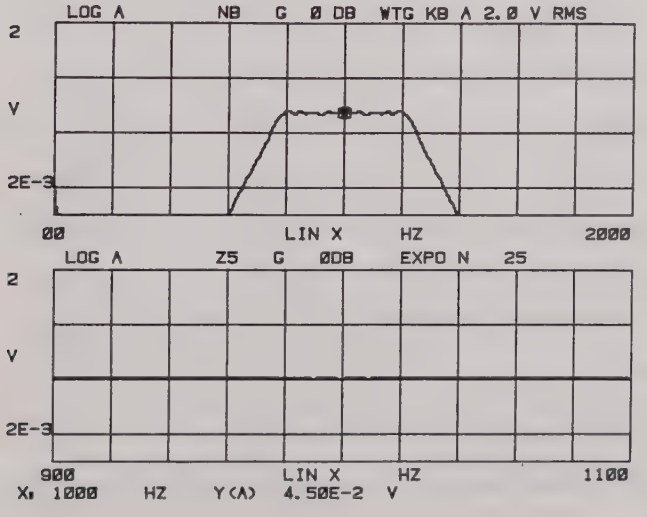


Figure 3-12. Dual Display of the BAND LIMITED Signal with the Lower Trace Showing Translated Data with a ZOOM of 5.

Press the AVERAGE (M1) group ERASE touch control, select ZOOM 10, press the AVERAGE (M1) group START touch control and compare the display with Figure 3-13.

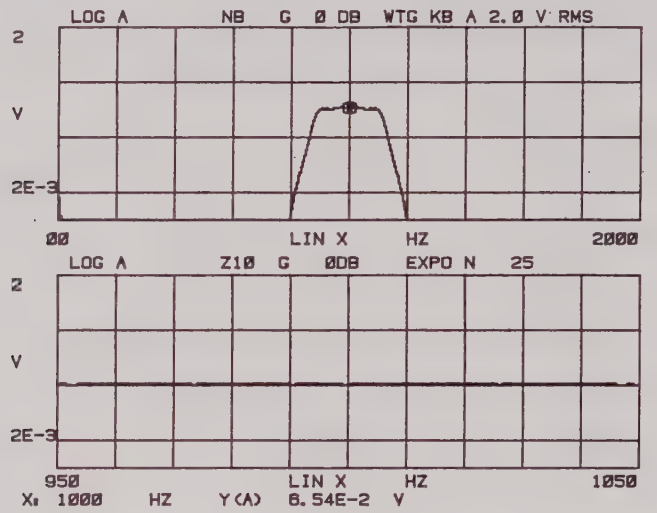


Figure 3-13. Dual Display of the BAND LIMITED Signal with the Lower Trace Showing Translated Data with a ZOOM of 10.

Press the AVERAGE (M1) group ERASE touch control, select ZOOM 20, press the AVERAGE (M1) group START touch control and compare the display with Figure 3-14.

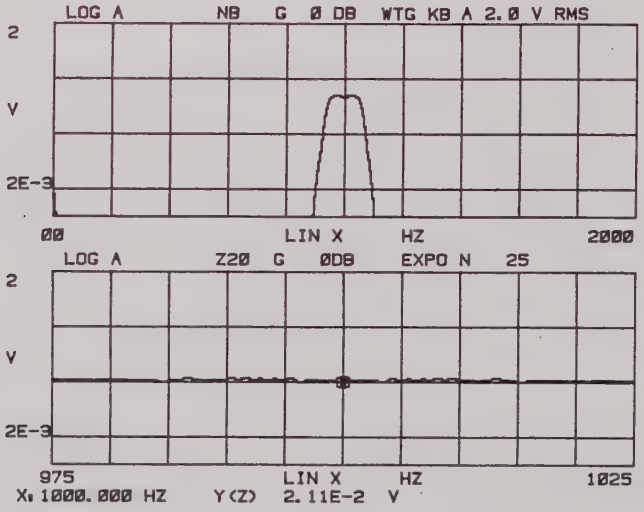


Figure 3-14. Dual Display of the BAND LIMITED Signal with the Lower Trace Showing Translated Data with a ZOOM of 20.

Press the AVERAGE (M1) group ERASE touch control, select ZOOM 50, press the AVERAGE (M1) group START touch control and compare the display with Figure 3-15.

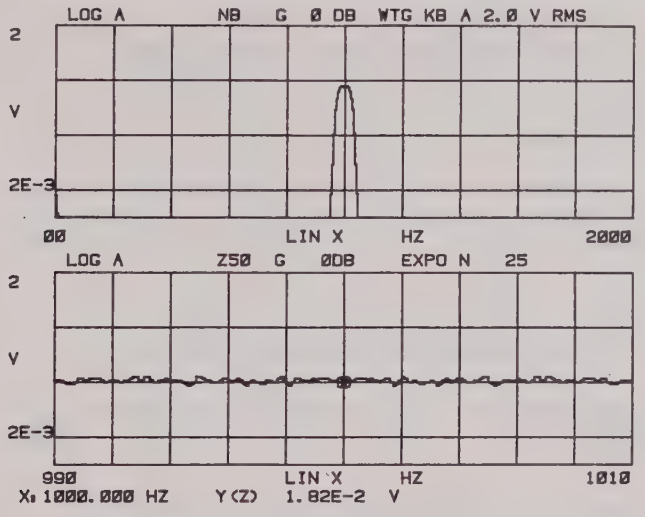


Figure 3-15. Dual Display of the BAND LIMITED Signal with the Lower Trace Showing Translated Data with a ZOOM of 50.

Press the AVERAGE (M1) group ERASE touch control, select ZOOM 100, press the AVERAGE (M1) group START touch control and compare the display with Figure 3-16.

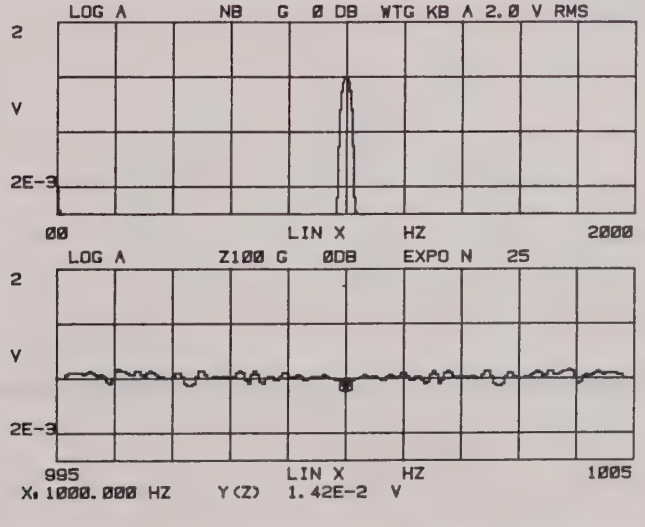


Figure 3-16. Dual Display of the BAND LIMITED Signal with the Lower Trace Showing Translated Data with a ZOOM of 100.

3.4.4 BROAD BAND CHECK

a. Press the following touch controls in the indicated sequence:

DISPLAY Group
1. Press RT, UPPER

PARAMETERS Group
1. Press PRGM, 6

FUNCTION Group
1. Press MENU, select BROAD BAND, press OPER

AVERAGE (M1) Group
1. Press ERASE

CH A & B Group
Using the FREQ UP/DOWN touch controls, select the 100 kHz frequency range.

CURSOR Group
1. Press ADRS

PARAMETERS Group
1. Press 400, ENT

CURSOR Group
1. Press ΔP

DISPLAY Group
1. Press M1

AVERAGE (M1) Group
1. Press START

Compare the display with Figure 3-17 and note the overall amplitude reads 5.00E-1 V RMS, ± 25 mv.

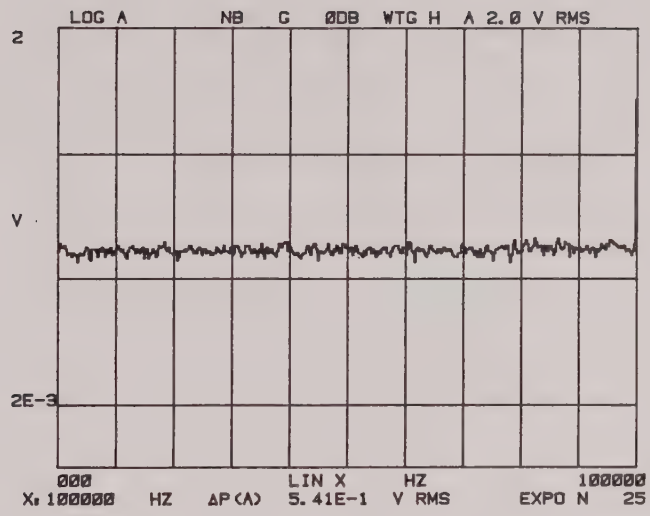


Figure 3-17. Averaged BROAD BAND Signal, 100 kHz Analysis Range, ADRS 400, ΔP Cursor Mode.

This concludes the Operational Checkout of the SD375 SSG (-4) Option. Application notes containing information related to the use of the SSG Option are included in Appendix A, located at the rear of the manual.

DYNAMIC ANALYSIS OF MACHINES AND STRUCTURES

Anton C. Keller
Vice-President, Technical Services
Spectral Dynamics
Scientific-Atlanta

Mr. Keller received the B.S.E.E. Degree from Manhattan College in New York City. He was employed at the White Sands Missile Range for seven years during which time he received the M.S.E.E. Degree from New Mexico State University. Prior to joining Spectral Dynamics Corporation in November 1965, Mr. Keller was group leader in charge of analysis of all environmental data gathered at the White Sands Missile Group. In his current position as Vice-President, Technical Services, Mr. Keller is responsible for corporate technical documentation, presentation of up-to-date information relating to new product applications, and developing and conducting technical training seminars. He is the author of several papers in the field of vibration and transfer function analysis and is a member of the San Diego Chapters of IES and IEEE.

The use of signals from transducers to diagnose rotating machinery and structural problems by spectrum analyzers has become an accepted technique. Typically, a bearing mounted displacement probe will provide a voltage signal proportional to relative motion of the shaft bearing or another location. Accelerometer signals from system components are also used to determine system parameters for design and modification of machines and structures. The transducer time data is analyzed for its information content most often by examining the frequency spectrum of the original time history signal. Such an analysis is usually performed by an FFT analyzer which effectively filters the signals with a discrete bandwidth over a desired frequency range.

Frequency Spectra

Figure 1 shows a typical frequency spectrum plot of operating data. In general, the spectrum peaks are the results of rotating components, or are associated with resonances within the system. Obviously, when a frequency of a rotating component happens to coincide with a frequency of a system resonance, the potential for peak amplification exists. Vibration problems associated with this condition have been the cause of many investigations. Usually, amplitude peaks associated with the rotating shaft are fixed multiples of the shaft speed; whereas, resonant frequencies are fixed and do not vary with shaft speed. Small variations in resonant frequencies sometimes occur when a change in shaft speed is accomplished by a large change in machine component stress or temperature.

Figure 1 may be considered a single snapshot of an operating spectrum taken from a case-mounted accelerometer on an operating compressor at about 3000 rpm during a speed-increasing run. To get a more complete picture of the operating characteristics, several such plots at various speeds would be useful. One way of representing a composite of frequency spectral data over an entire speed range is a three-dimensional spectrum display of amplitude vs. frequency vs. time. Several methods for doing this are available. One such representation is shown in Figure 2.

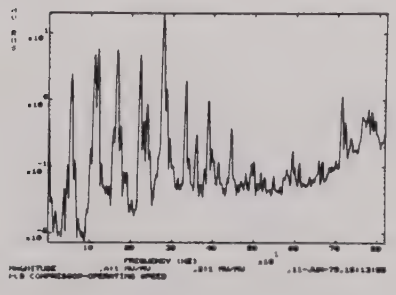


Figure 1. Operating Spectrum

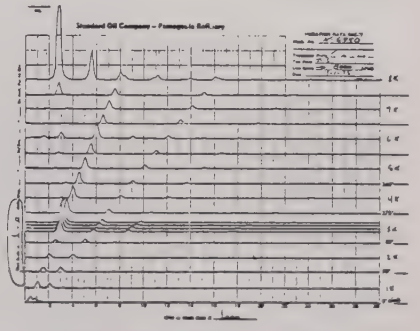


Figure 2. Manual 3-D Spectrum Display

3-D Displays

In this example, machine speed increased from 500 rpm to 8,000 rpm with a spectrum scan taken at 500 rpm increments. The results were placed one above the other in order of increasing speed. The "1 times rpm" component is seen to increase dramatically in amplitude as the machine passes through a resonance which was identified as a shaft critical.

Another example of three-dimensional spectra resulting from computer acquisition data analysis is seen in Figure 3. Here, an accelerometer mounted near a compressor bearing monitored vibration during a speed-decreasing run from 3,000 rpm to approximately 500 rpm. Data was taken generally every 80 rpm during this run, but at one point in the middle of the run, shaft speed change was so rapid, several "holes" appear in the display.

Campbell Diagram

In some cases, is is desirable to place a threshold (minimum amplitude limit) on the data to concentrate attention only on important data. One method of presenting this type of data is a Campbell diagram such as Figure 4. This plot of frequency vs. machine speed vs. amplitude of response may have circles superimposed on the diagram, with the diameters of the circle representing signal amplitude at the respective frequency and machine speed. Note, that a vertical cut at a single speed provides the same data as a spectrum plot of that speed.

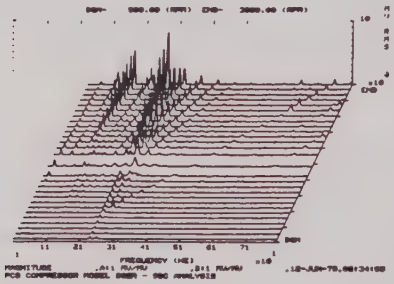


Figure 3. Computer Generated Spectrum Display

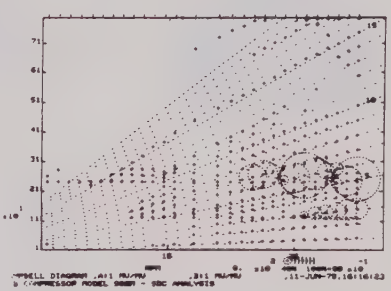


Figure 4. Campbell Diagram

On the Campbell diagram, rows of circles are located on either the diagonal rotational order lines, or along horizontal lines. The high amplitudes along the order lines are related to forces associated with the rotating components, and if these amplitudes are excessive, they may indicate fault conditions. On the other hand, the rows of circles along the horizontal lines represent high amplitudes present over a band of machine speeds, but within a narrow frequency region. This indicates that a resonance within the structure is being excited. When the two types of rows intersect, the vibration is amplified by the system resonance. If the usual operating speed of the machine is near the speed at which this resonance appears, the design may require modifications to alter the resonance, so that vibration is diminished or eliminated. The crux of the problem centers on determining the best modification. In order to to this, several approaches may be taken to identify resonances and correct the problem.

Transfer Function Measurement

An accurate measurement of a transfer function may positively identify the resonant frequencies of a structure. The measurement of transfer functions over the coordinate system of a structure provides the data for constructing the mode shape at each resonant frequency. Basically,

$$\text{Transfer Function} = \frac{\text{System Output}}{\text{System Input}}$$

The transfer function is frequency dependent and a rigorous definition requires that the phase relationship between input force and the output be included.

Measuring transfer functions on a static system is normally a routine task. Force input is generated by using a swept sine, random or impact excitation. A diagram of instrumentation for performing transfer function measurements is shown in Figure 5. Fundamentally, a two channel FFT analyzer performs a spectrum analysis on each of 2 signals; for this example, force and acceleration values. Then, the numerical ratio and phase are computed and the results are displayed as magnitude and phase plots. Attempts to determine resonant frequencies without using a two-channel measurement can lead to error. For example, Figure 6 shows an accelerometer spectrum and one would assume from the data shown that there is a resonance at 1420 Hz. However, the force spectrum reveals that the force also peaked at 1420 Hz and that this force is the true cause of the acceleration peak. The true transfer function shown in Figure 7 reveals that no resonance exists at 1420 Hz, but that the resonance peak is at 1510 Hz.

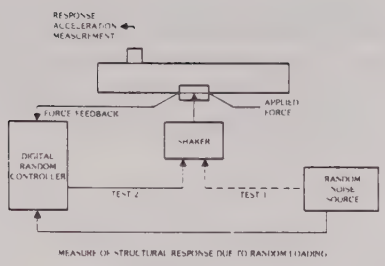


Figure 5. Transfer Function Block Diagram

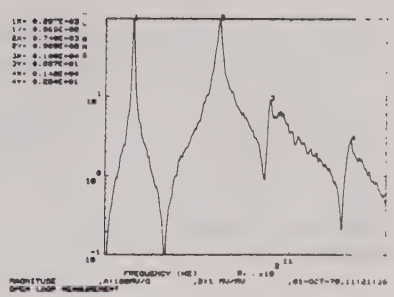


Figure 6. Open Loop Acceleration Response

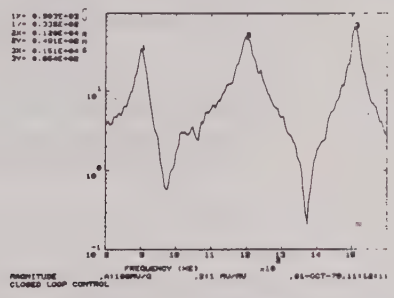


Figure 7. Transfer Function — Tone Resonances — Closed Loop

This problem may be eliminated by controlling the force via a servo loop to a constant level. Figure 5 shows the control loop for controlling force during a random excitation. The impact technique obviates the problem by eliminating the shaker and its particular characteristics. An impact, theoretically, is one which has infinite amplitude and is of infinitesimal short duration. Such an idealized impact has an absolutely flat spectrum and as a result all resonances would be excited. It is possible for impacts under practical test conditions to have a flat spectrum over the range of interest. For example, in many engineering structures, resonances beyond 5,000 Hz are of no concern. A good steel tip on an impact hammer can provide a very flat force spectrum within this range. Note, that in Figure 4, all obvious resonances (frequencies where a horizontal series occurred) are below 5,000 Hz. Therefore, a single channel measurement using an impact excitation may be used to identify resonant frequencies. However, this is of no value in doing a modal study since the acceleration amplitude is dependent on the magnitude of each individual impact. For mode shape determination, the true transfer function including phase must be measured.

As mentioned earlier, the two channel transfer function measurement is a common and straightforward measurement to make. However, suppose it is desired to measure transfer functions on a rotating machine which cannot be shut down. Ordinarily, this would not be possible, because the response signal would contain not only the response due to intentional excitation, but also response due to the forces of the machine's rotating components.

Synchronous Transfer Function

A new technique, synchronous transfer function measurements, now permits measurements directly on operating systems. This technique uses a pseudorandom excitation and time averages applied force and response acceleration with respect to the pseudorandom repetition interval. Since pseudorandom sources provide a repetitive sync pulse which is completely independent of the operating system being analyzed, averaging the time blocks of force and acceleration will completely eliminate operating system components. After an adequate number of blocks of both signals are averaged, the Fourier transform of each signal is taken. The ratio of the resulting transforms is the synchronous transfer function in which the structure's true broadband characteristics have been extracted from the operating environment.

Figure 8 provides an example of the force and acceleration spectra from an operating machine to which a random force input was applied. Note, that the operating components almost completely mask the broadband effect of the random input. The resulting transfer function of Figure 9

is totally in error and provides no useful information. An averaged time signal synchronized with the pseudorandom repetition rate is given by Figure 10. The corresponding Fourier transforms of force and acceleration are shown in Figure 11. The effects of the rotating components of the machine have been removed from the signals and the spectra are the result of the pseudorandom excitation only. A comparison of Figure 12, which is the synchronous transfer function, with Figure 13, which is a transfer function measurement on the nonoperating system, reveals that an acceptable measurement has been made.

Comparison of Transfer Functions

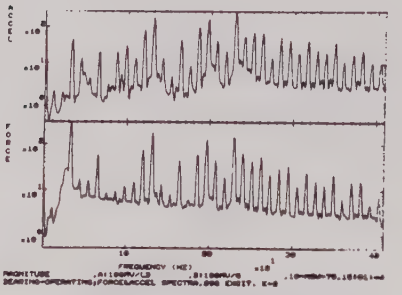


Figure 8. Acceleration and Force Spectra

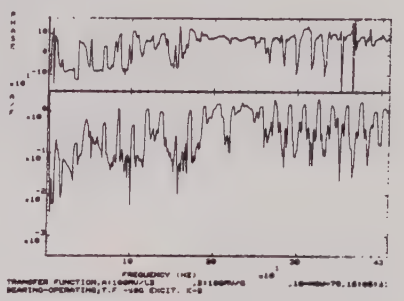


Figure 9. Transfer Function — Operating System

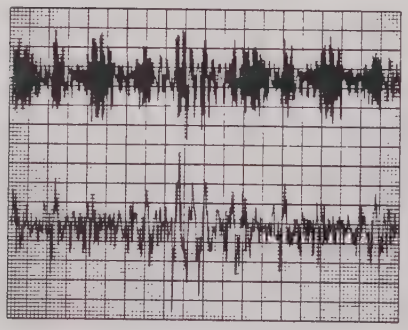


Figure 10. Time-Averaged Force and Acceleration

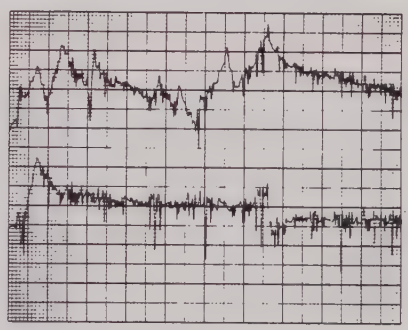


Figure 11. Synchronous Spectrum Force and Acceleration

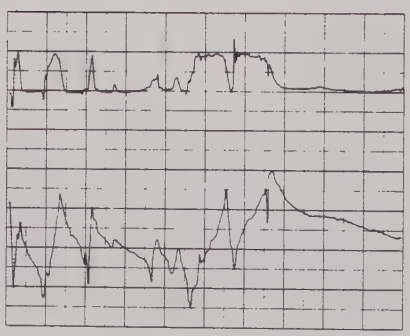


Figure 12. Synchronous Transfer Function — Operating System

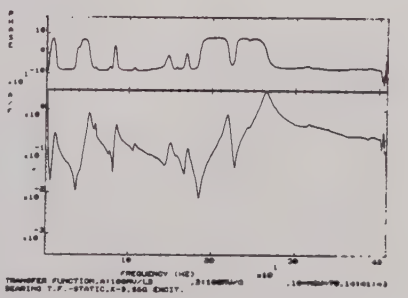


Figure 13. Transfer Function — Nonoperating System

Computerized Modal Analysis

In order to fully determine the dynamic response of a mechanical system, two techniques are available to the engineer. One of these is an analytical approach; the other uses test data typically generated in the laboratory. If an analytical approach is employed, it is often possible to determine many vital modal parameters including resonant frequencies, deformation patterns and predicted system interconnection dynamics. It may prove difficult to determine damping characteristics but, nevertheless, valuable design data can often be accurately estimated, with this method. Even if an analytical approach is used, however, it is usually desirable to verify the results of a design by measuring actual system dynamic parameters. A testing approach can thus be employed to create a system model based on an interpretation of measured frequency response functions and extracted system characteristics. If sufficient information is obtained from the test data, a testing model can be established and used quite accurately to determine prototype behavior and predict the effects of design modifications.

Test Setup

In most cases, if a testing model is to be created, an external or artificial system stimulus will be provided. The excitation can take many forms including periodic, random or transient waveforms. However the excitation must adequately cover the desired frequency region to assure that each possible frequency of system dynamic weakness is indeed excited. Depending on the type and size of the structure to be tested, it may be necessary to use a form of shaker excitation. For many smaller structures or system components, impact excitation has proved quite effective especially for simple extraction of structural mode shapes. In some cases, actual system self-excitation can provide sufficient excitation for frequency response measurement or, as previously seen, system self-excitation can sometimes represent the equivalent of unwanted noise. In the extreme, very large structures may require very large force excitation levels; such as, several tons of concrete blocks suspended adjacent to the structure of interest and impacted like a huge pendulum.

If a shaker is used to apply a sine sweep or broadband excitation, an important consideration may be the point of attachment of the vibration pickup. The major consideration here is that the point of application of the forcing function should not be at a nodal point for one of the important modes. Intuitively, before the modal study is done, the modes are not known. Therefore, to be sure that an important mode is not missed, a second excitation point should also be selected and checked. When using the impact technique, this also applies to the response accelerometer location.

Test Model Geometry

When describing a system to be tested by computerized modal analysis, a fundamental starting point is to describe an adequate coordinate system. Depending upon the shape of the system being described, the most convenient coordinate system might be rectangular, spherical, cylindrical or a combination of several systems. Ultimately, the definition reduces to a description in space of a series of points having unique spatial locations. Although the temptation is great to specify large mechanical systems in minute detail, experience has shown that most systems can adequately be described by less than 150 points, in some cases much less. A typical set of locations describing a sealed compressor is seen in Figure 14. In this example, 42 points taken from drawings of the compressor with two views were used to fully describe the test object.

Once the geometry for a structure has been defined, a representation of the structure is stored in the computer in terms of a series of points in space. In order to give the computer model of the test object a realistic shape, it is necessary to define an interconnecting algorithm among the various geometry points. Since there is more than one way to interconnect a given set of locations, several different looking structures could be pictured from the same geometry set. A typical interconnecting sequence for the points in space describing the compressor is shown in Figure 15. The series of trace locations shown simply move from point to point to form a connection sequence.

GEOMETRY

LOC	X	Y	Z				
1	0	0	0	23	80	-27	-40
2	10	50	0	24	80	0	-43
3	10	27	40	25	80	27	-40
4	10	0	43	26	131	50	0
5	10	-27	40	27	131	27	40
6	10	-50	0	28	131	0	43
7	10	-27	-40	29	131	-27	40
8	10	0	-43	30	131	-50	0
9	10	27	-40	31	131	-27	-40
10	35	50	0	32	131	0	-43
11	55	27	40	33	131	27	-40
12	35	0	43	34	151	50	0
13	35	-27	40	35	151	27	40
14	35	-50	0	36	151	0	43
15	35	-27	-40	37	151	-27	40
16	35	0	-43	38	151	-50	0
17	55	27	-40	39	151	-27	-40
18	80	50	0	40	151	0	-43
19	80	27	40	41	151	27	-40
20	80	0	43	42	176	0	0
21	80	-27	40	**			
22	80	-50	0				

Figure 14. Geometry of the System Model

#LTL
LOCATIONS

1	2	10	18	26	34	42	0	1	3	11	19
27	35	42	0	1	4	12	20	28	36	42	0
1	5	13	21	29	37	42	0	1	6	14	22
30	38	42	0	1	7	15	23	31	39	42	0
1	8	16	24	32	40	42	0	1	9	17	25
33	41	42	0	2	3	4	5	6	7	8	9
2	0	10	11	12	13	14	15	16	17	18	0
18	19	20	21	22	23	24	25	18	0	26	27
28	29	30	31	32	33	26	0	34	35	36	37
38	39	40	41	34	0						
0											

Figure 15. Links of the System Model

When the interconnecting links have been established, the computer-generated version of the structure under analysis is then available for static viewing. One such view of the compressor is shown in Figure 16. Since the structure is represented as a series of interconnected points in space, the observer can rotate the representation so as to position himself at virtually any point he chooses for observing the test item. In some cases, it can be of great help to the test engineer to be able to see the computer version of the test object from various angles. This is possible by observing the object along the three major axes plus from some selected isometric viewing angle. Four such views of the compressor are shown in Figure 17.

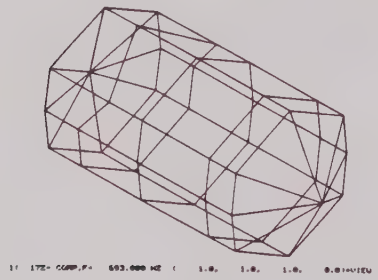


Figure 16. Compressor Static View

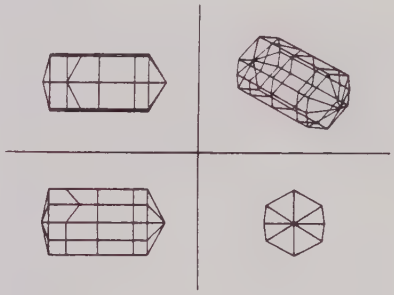


Figure 17. Composite Static Views

Test Locations

After a test object has been described to the computer, it is then necessary to select the desired sequence of locations where excitation is to be applied and, of course, the type of excitation to be used. Alternatively, if shaker excitation is to be employed and various response locations measured, the sequence of response locations should be quantitatively described. Excitation and response measurements can then be made in either a single direction or three-dimensionally as shown. A typical sequence of testing locations giving position, axis and sense is shown in Figure 18.

```
SLTC
COORDINATES
   1X+   2Y-   3Z-   4Z-   5Z-   6Y+   7Z+   8Z+   9Z+  10Y+
  11Z-  12Z-  13Z-  14Y+  15Z+  16Z+  17Z+  18Y-  19Z-  20Z-
  21Z-  22Y+  23Z+  24Z+  25Z+  26Y-  27Z-  28Z-  29Z-  30Y+
  31Z+  32Z+  33Z+  34Y-  35Z-  36Z-  37Z-  38Y+  39Z+  40Z+
  41Z+  42X-
E
```

Figure 18. Testing Location Coordinates

Frequency Response Function Measurement

A complete dynamic description of the structure being tested can be obtained if frequency response functions are measured and recorded between each of the testing locations and a common reference point. Figure 19 gives a system matrix which is the frequency response function. Two elements of a matrix related to a common reference point can be related to each other by the laws of superposition and transposition. It is necessary in a modal testing sense to measure either one row or one column of a total system matrix.

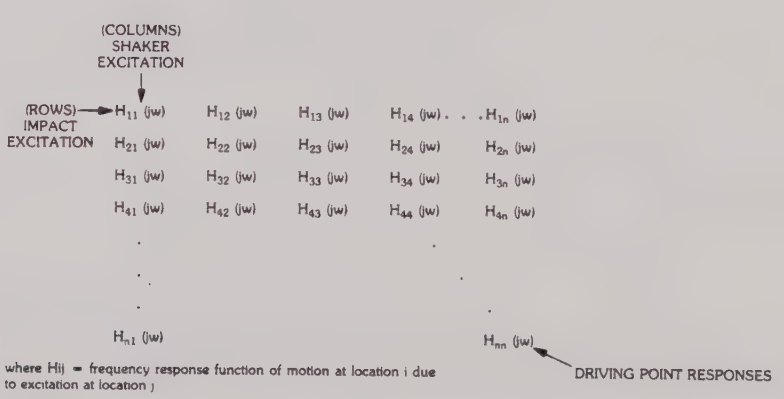


Figure 19. System Frequency Response Function Matrix

Data Directory

The directory of a typical set of data taken during a test such as the compressor test described is shown in Figure 20. The stored sequence indicates a fixed accelerometer location, for this example 17Z-, and a variable impact point.

```
# RECORDS IN USE
REC    1  17Z-  1X+   0
REC    2  17Z-  2Y-   0
REC    3  17Z-  3Z-   0
REC    4  17Z-  4Z-   0
REC    5  17Z-  5Z-   0
REC    6  17Z-  6Y+   0
REC    7  17Z-  7Z+   0
REC    8  17Z-  8Z+   0
REC    9  17Z-  9Z+   0
REC   10  17Z-  10Y+  0
REC   11  17Z-  11Z-  0
REC   12  17Z-  12Z-  0
REC   13  17Z-  13Z-  0
REC   14  17Z-  14Y+  0
REC   15  17Z-  15Z+  0
REC   16  17Z-  16Z+  0
REC   17  17Z-  17Z+  0
REC   18  17Z-  18Y-  0
REC   19  17Z-  19Z-  0
REC   20  17Z-  20Z-  0
REC   21  17Z-  21Z-  0
REC   22  17Z-  22Y+  0
REC   23  17Z-  23Z+  0
REC   24  17Z-  24Z+  0
REC   25  17Z-  25Z+  0
REC   26  17Z-  26Y-  0
REC   27  17Z-  27Z-  0
REC   28  17Z-  28Z-  0
REC   29  17Z-  29Z-  0
REC   30  17Z-  30Y+  0
REC   31  17Z-  31Z+  0
REC   32  17Z-  32Z+  0
REC   33  17Z-  33Z+  0

#
REC   34  17Z-  34Y-  0
REC   35  17Z-  35Z-  0
REC   36  17Z-  36Z-  0
REC   37  17Z-  37Z-  0
REC   38  17Z-  38Y+  0
REC   39  17Z-  39Z+  0
REC   40  17Z-  40Z+  0
REC   41  17Z-  41Z+  0
REC   42  17Z-  42X-  0
##
```

Figure 20. Data Directory of Records in Use

Mode Parameters

Once a frequency response function has been measured, it can be viewed and its accuracy qualified prior to being stored as part of the system data base. If it is apparent that valid data has been recorded, the measured frequency response function can be placed on the mass storage media. After a sequence of frequency response functions has been measured and stored, the next step is to begin extracting the parameters necessary to characterize the structure in terms of its dynamic properties.

Figure 21 shows a typical frequency response function measured on the test compressor using impact excitation. For this measurement, the response accelerometer was located at position 17 with its axis of sensitivity along the negative Z axis. The excitation for this measurement was at location 14 in the positive Y direction. The resulting accelerance, which is the ratio of the measured acceleration response to input force, is displayed.

Figure 22 shows three peaks in the frequency response which correspond to apparent resonances. A 90 degree phase shift is present at the frequency of each of these peaks, indicating that a natural frequency has indeed been excited. Frequencies of interest in the region of 624 Hz, 694 Hz and 790 Hz are marked and listed.

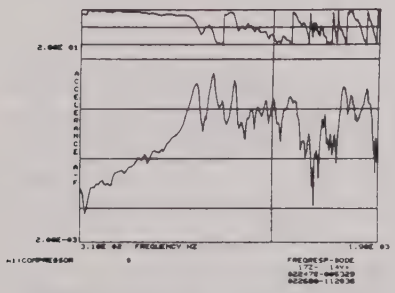


Figure 21. Compressor Frequency Response Function

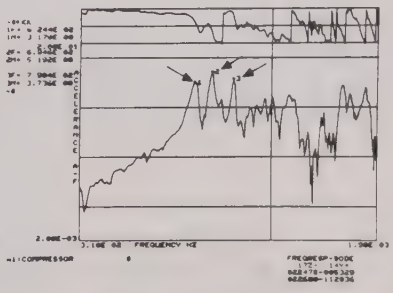


Figure 22. Resonant Peaks

Based on measured data, the key parameters which must be extracted include the system resonant frequencies, the damping values at resonance and the system deformation patterns or mode shapes at each of the extracted resonant frequencies. Although these values can sometimes be determined directly from the measured data, it is often more attractive from both an instrumentation and a signal processing standpoint to generate a series of broadband frequency response functions and to determine the other desired parameters through a curvefitting

technique. From a practical standpoint, the accuracy with which a resonant frequency can be determined is directly related to the frequency resolution of the processing system. If a frequency response measurement up to 1 kHz is required, analysis resolution will typically be on the order of 2 to 2.5 Hz. From a system standpoint, especially if component substructuring is to be performed, this degree of resolution is often not sufficient to establish a complete dynamic model.

Frequency Resolution Improvement

To achieve improved resolution, two choices exist. Either a "zoom" type of analysis can be performed in which the full resolving power of the FFT processor is placed within a narrow frequency region, or a technique of curvefitting the broadband response can be employed. If the zoom approach is used, the data usually must be reprocessed at each of the resonant frequencies of interest. Depending upon the amount of mass storage available for the analysis system, data may have to be separately acquired at each of the resonant frequencies. This lengthens the testing and data acquisition phase and requires relatively complete analysis capability right at the test site. In order to increase analysis resolution by a factor of 10 using a zoom approach, the actual data acquisition time is also increased by a factor of 10. If ten system modes are to be extracted, this can represent a potentially unnecessary burden on the personnel performing the instrumentation and testing phase. However, in cases where modes are closely coupled or where an extremely high modal density exists, the zoom approach is both necessary and effective.

Single-Degree-of-Freedom Curvefit

For the compressor measurements described in our examples, a frequency range of 2,000 Hz was used and the processing transform size selected to give a basic resolution of 4 Hz. In order to improve the accuracy of the system dynamic model, two types of curvefitting were employed. The first of these is seen in Figure 23 and represents a simple least squares error circular curvefit. In this example, the frequency region from 688 Hz to 705 Hz for the same frequency response function as seen in Figure 21 was selected and the curvefit displayed in the form of a Nyquist diagram superimposed on the original test data. Here, the real part of the frequency response function and corresponding curvefit are displayed on the abcissa and the imaginary part on the ordinate. It can be seen that, within this region of 17 Hz, five analysis cells or resolution elements are present, each indicated by a small circle. The large circle, representing the single-degree-of-freedom curvefit, passes through most of the actual analysis frequencies and is more or less centered on the vertical (imaginary) axis indicating that a relatively pure mode was excited within this frequency region with a minimum of coupling activity from adjacent modes. This, of course, is verified by the Bode diagram seen previously in Figure 21.

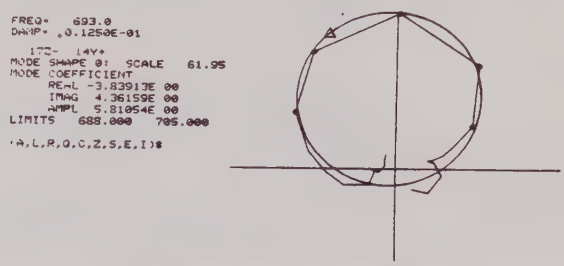


Figure 23. Single-degree-of-freedom Curvefit

Note, that since acceleration and force measurements are being used, a condition of resonance is typified by a nearly exact 90 degrees phase relationship between the acceleration and force vectors at the resonant frequency. The maximum vector at resonance, thus, nearly coincides with the vertical axis for the pure, uncoupled mode situation as illustrated in this example. The diameter of the circle generated through this curvefitting technique represents the contribution at this particular resonant frequency at location 14, which is identified as mode No. 1. By performing at each location tested a series of such curvefits, each resonant frequency can be examined and the contribution in terms of scaled relative motion determined for each point at each of the selected resonant frequencies. By mapping this contribution as a function of each point on the model, the mode shape for each resonant frequency can thus quickly be determined. This can then be stored in an active mode shape file for subsequent display in either a static or animated fashion.

Multi-Degree-of-Freedom Curvefit

Although damping can be estimated directly from a single-degree-of-freedom curvefit from the real and imaginary components of a measured frequency response function, the lack of resolution previously discussed often makes this a relatively ineffective approach. A more effective way of accurately estimating structural damping without the use of a zoom processing approach

is available through the use of a multi-degree-of-freedom root extraction algorithm. An example of one result of using this approach is seen in Figure 24. Here, the frequency region from 500 Hz to 900 Hz has been visually expanded for viewing purposes. Within this region, a series of eight roots (solutions to the equations of motion governing the frequency response function behavior over this region) were extracted. After root extraction, a frequency response function corresponding to these roots was then generated and compared with the original test data. For the example shown in Figure 24, this comparison indicates a damping characteristic for the third mode which is somewhat lower than that measured. In many cases, this is not unexpected, since in the process of making the frequency response measurement, additional damping is sometimes contributed by the measurement. Also, in some cases, the actual system resonance may not occur at the center of an FFT bin because of the finite resolution of the FFT process. Nevertheless, the general match between measured and curvefit data in terms of both magnitude and phase is quite good. This signifies that the extracted modal parameters in terms of resonant frequency, damping, response magnitude and phase have been estimated with consistent accuracy.

Figure 25 shows the parameters extracted for the three modes originally identified. The two dynamically strong modes appear to be those at approximately 693 Hz and 790 Hz. These two modes which represent primarily compressor casing response show damping factors of 0.6% and 0.1%, respectively.

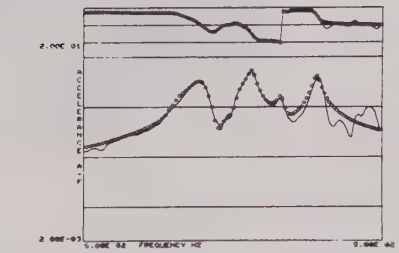


Figure 24. Multi-degree-of-freedom Curvefit

MODE PARAMETERS								
LABEL	FREQ	DAMPING	AMPLITUDE	PHASE	REF	RES	MODE	FLAGS
1	625.247	0.016442	281.6	-2.6681	172-	14V+	1	0 0 0 0 0
2	695.248	0.006093	179.5	1.6374	172-	14V+	2	0 0 0 0 0
3	791.623	0.000991	80.04	-1.9281	172-	14V+	3	0 0 0 0 0

Figure 25. Mode Parameters

Once mode shapes have been calculated, they can be displayed statically or dynamically in any one of a number of ways. For static viewing, a selected deflection position can be viewed by itself, or the same deflection may be viewed from four separate viewing angles. Examples of each type of display for the compressor are shown in Figure 26 — 30. From a dynamically animated standpoint, usually virtually any viewing position from which to observe an animated mode shape display may be selected. For the 693 Hz compressor mode, it is readily apparent that the upper right and lower left portions of the compressor casing oscillate out of phase with a significant difference in magnitude. For the designer of this compressor, the motion at this resonant frequency was quite important from an acoustical radiation standpoint and also due to the fact that additional structures were to be coupled to the compressor with a more than likely transmission of vibration at these frequencies at several attachment points.

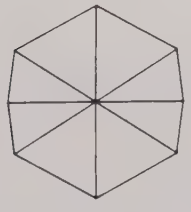


Figure 26. Undefined End View

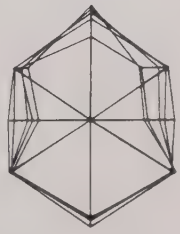


Figure 27. Defined End View

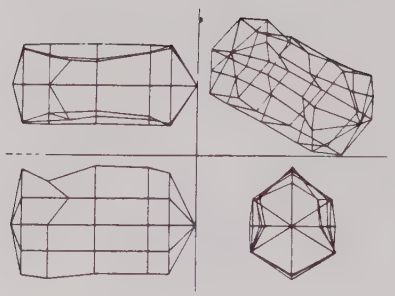


Figure 28. Static Views-Up

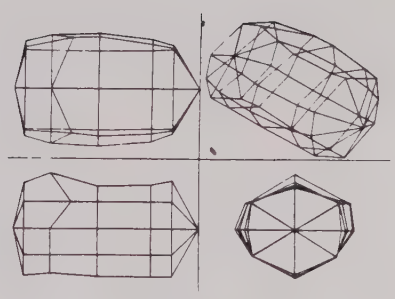


Figure 29. Static Views — Down

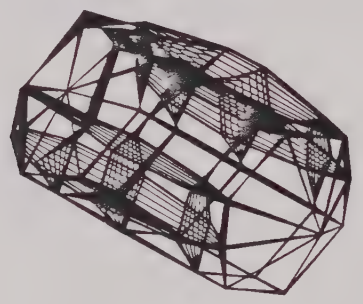


Figure 30. Animated Modes

Building Block System Modeling

If several substructures are to be interconnected, a knowledge of the individual dynamics of each structure can be used to predict overall system response using a building block dynamic combination approach. The true power of system modeling is exhibited when it is possible to predict overall system response based on making slight changes to one of the mechanical elements in the system. This, then eliminates the necessity of building and testing multiple prototype structures. To assist in interpretation of the possible effects which might occur when modifications to a system are performed, many reliable guidelines have been established. Some of the more important of these follow.

- Resonances and anti-resonances must alternate as a measured frequency response function is traversed from low to high frequency, for driving point transfer functions.
- The addition of a single mass to a system decreases all nonzero resonances where the connection point participates. The original resonant frequencies of the higher modes tend to shift more dramatically. As the frequency becomes extremely high, the new resonant frequencies approach the anti-resonances of the original component at that location.
- The addition of a single spring to a component increases the frequency of all resonances in which the connection point participates. The resonant frequencies of the lower modes tend to shift more dramatically. As the frequency approaches zero, the new resonances approach the anti-resonances of the original system.
- When two systems are connected through a single weak spring, the resonances of the combined system will occur near or at slightly higher frequencies than the resonances of the separate systems. If two resonances of the separate systems are close together, two corresponding resonant frequencies of the combined system result. One of which is located between the two separate resonances. The other resonant frequency is located slightly higher than either of the resonances of the separate systems.

Conclusion

Frequency response function measurements can be made either for the purpose of rapidly establishing a series of structural values or with the idea in mind of creating a complete system dynamic model. If a complete model is established using a computerized system it is often possible to model system characteristics and produce the effects of subtle system variations without having to actually build the new system and test a new prototype.

Once measurements have been completed, and the modal parameters extracted, many uses for this valuable information exist. In rotating machinery application, a knowledge of the structural resonant frequencies can be used to more logically interpret operating data such as Campbell diagram and three-dimensional displays. Obviously, a knowledge of the mode shapes assists the designer or troubleshooter in applying the optimum fix to a machine with a vibration problem. It can be said that the frequency response function defines the problem and a carefully analyzed mode shape points toward the necessary solution. A knowledge of dynamically weak and stiff points on an operating machine can also facilitate the location of optimum points for transducers for machinery monitoring.

If the mode shape of a troublesome resonance can be determined while the machine is operating, preparations for modification can be made prior to a scheduled shutdown. Frequently dynamic characteristics change when a machine is under operating stress and temperature making the ability to make synchronous transfer function measurements a definite advantage for data analysis.

A carefully performed modal analysis will assist a designer or system operator in several ways.

- The characteristics of an original system or initial design can be described quantitatively and any deviations from these characteristics easily ascertained.
- The effects of making changes to an existing system can often be predicted quite accurately without the need for repeating an expensive testing sequence.
- If several substructures are to be interconnected, the resulting dynamic behavior of the total system can often be predicted without the need for repeating a measurement sequence.
- Interpretation of operating data and optimization of monitoring procedures can often result from a thorough understanding of system dynamic behavior.

DETECTING, ENHANCING OR ELIMINATING SIGNALS

IN NOISE

Scientific-Atlanta

Spectral Dynamics Division

United States: P.O. Box 23575 • San Diego, CA 92123-0575 • (619) 268-7100 • TWX 910-335-2022
Europe: Horton Manor • Stanwell Road • Horton, Slough, SL3 9PA, England • Telephone: Colnbrook 3211 • Telex: 849406

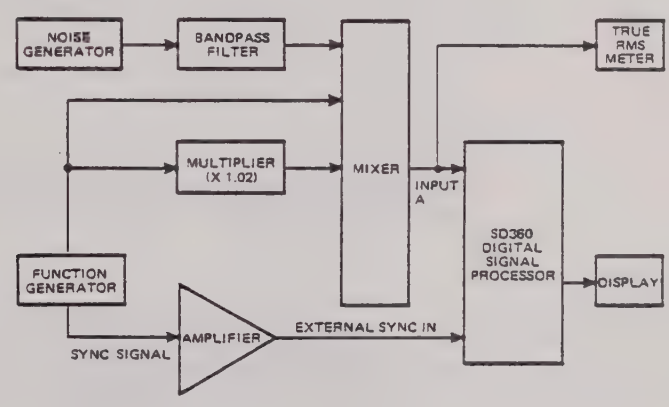
Detecting, Enhancing or Eliminating Signals in Noise

SIGNAL-TO-NOISE ENHANCEMENT

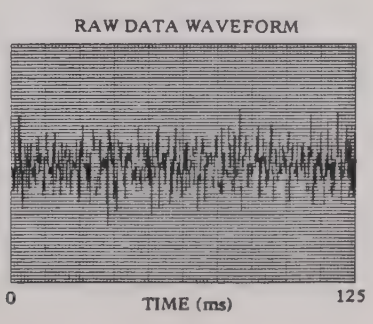
Reasons for improving signal clarity

One of the goals of many signal processing tasks is to improve a desired signal's clarity with respect to background noise. The reasons for wanting to improve signal-to-noise ratios vary widely. For example, they might include establishing the existence of a signal; determining the harmonic structure of a signal when only its fundamental component is known; improving speech intelligibility; determining the precise frequency of a signal when by nature it is only barely visible in the spectrum; or removing extremely high level signals of a precisely known frequency, but of an unwanted nature, such as an unbalance component, hum, line frequency component, etc.

Signal enhancement techniques can be applied in the time and frequency domains. To compare the effectiveness of various signal-to-noise enhancement techniques, a common test signal will be used for each approach. The equipment setup for this example is below.



The test signal is several periodic waveforms mixed with a shaped noise component. The time waveform of the signal is below. Regardless of the type of signal processing which is to be performed, it is good practice to first observe the raw data signal in the time domain. For certain types of signals, which include transient characteristics or occasional extremely high level values, observation of the time waveform will often reveal characteristics which will not be at all obvious after some type of signal processing or averaging is performed.



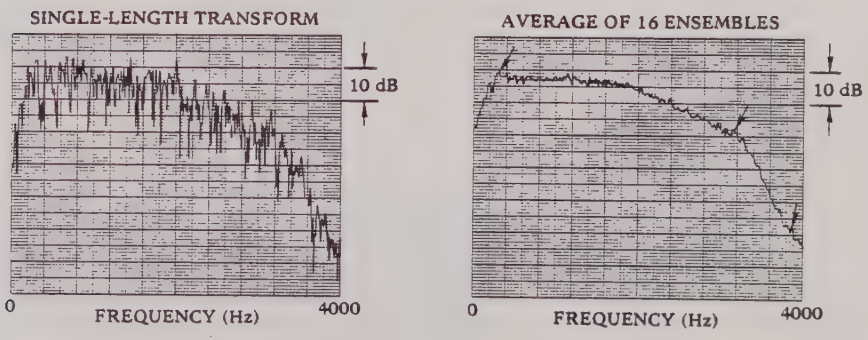
Averaging versus analysis bandwidth reduction

For many applications, the process which is most meaningful in terms of relating signals back to physical occurrences is that of performing a spectrum analysis. In addition to giving information about the frequencies of occurrence in the signal being measured, a simple spectrum analysis gives some signal-to-noise enhancement, which is related to the ratio of the signal bandwidth to the analysis bandwidth. If an analyzer is used which uses a sampling process, such as a real time analyzer (RTA) or fast Fourier transform (FFT) processor, the signal to be analyzed is normally passed through a low-pass or aliasing filter. In this case, the signal bandwidth corresponds to the bandwidth of the aliasing filter. The analysis bandwidth is determined by the number of lines (number of data points/sampling index) in the analyzer or processor. In general, the signal-to-noise enhancement produced under these conditions is

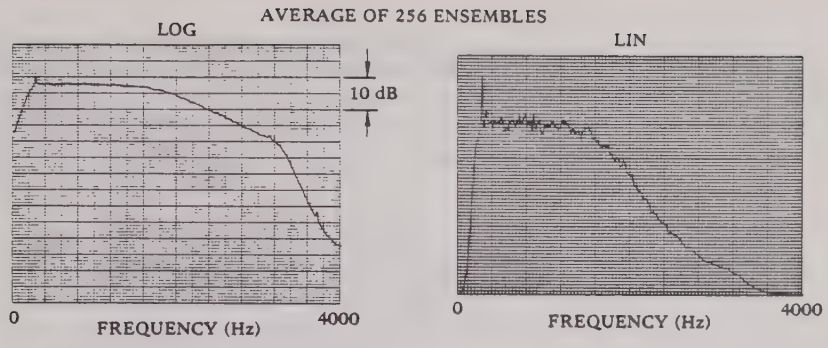
$$S/N_{enh} = \sqrt{\frac{BW_{signal}}{BW_{processor}}}$$

In the composite signal being used here, the levels of the various signals included are 0.088V rms for the 287 Hz periodic signal, 0.084V rms for the square wave of 299 Hz, and 0.74V rms for the shaped noise signal. The result of performing a single-length transform on the test signal is seen below. This is the equivalent of providing a "real time" snapshot of the spectrum present in the waveform over a frequency range of 0 to 4 kHz. Note that in this spectrum display, a broad, overall shape can be seen, but with the possible exception of the spectrum component at 290 Hz, no evidence of periodicities can clearly be determined.

If spectrum averaging is now performed, the existence of the periodic tones in the noise background is more easily verified. This is seen in the figure below which is the average of 16 ensembles of the test signal. Several of the tones are now visible.

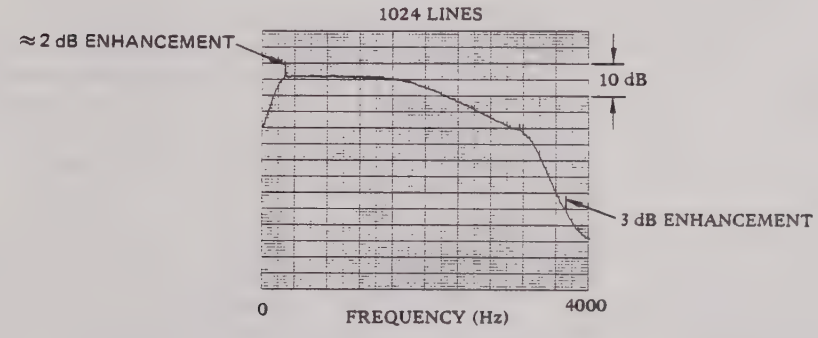


If additional spectrum averaging is performed, what improvements can be expected? The next figures show the same signal spectrum after 256 ensemble averages. Note that the increased averaging time has smoothed out statistical variations of the noise characteristic, and in this sense, has caused the periodicities to stand out somewhat more clearly than the previous spectrum of 16 averages. However, from the previous definition of signal-to-noise enhancement in the frequency domain, it is clear that enhancement is directly related to the ratio of bandwidths and is not directly related to averaging-time considerations. It is evident that additional signal-to-noise enhancement in the frequency domain is only possible by reducing analysis bandwidth at the expense of increasing analysis time.



Effect of transform length

Increased enhancement is also achieved by increasing the number of spectrum lines developed within any given frequency interval. In an FFT processor, this is equivalent to increasing the length of the transform. The previous figures showed spectrum analyses produced with 512-line resolution. Processing the same signal over the same frequency range with twice the resolution (1024 lines) gives the figure below.



A maximum signal-to-noise increase of 3 dB can be achieved, which is dependent on the relationship between the exact frequencies of any periodicities present and the precise center of the analysis windows created by the FFT process. In this figure, it is obvious that there is the full 3 dB enhancement at the harmonic shown at 3730 Hz. Whereas, in the region of the fundamental, there is approximately 2 dB enhancement.

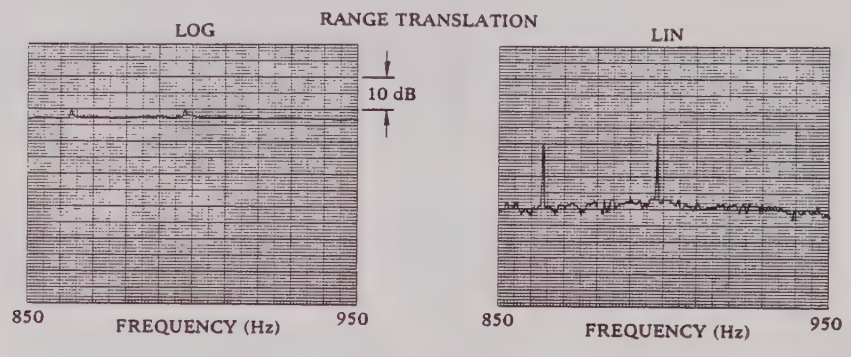
FREQUENCY TRANSLATION (ZOOM)

Analysis filter bandwidth reduction

Since signal-to-noise enhancement in the frequency domain is seen to vary in direct proportion to analysis filter bandwidth, an obvious way to improve signal enhancement is to provide the narrowest possible analysis window over a given selected frequency range. This can be done by either increasing the number of analysis lines, usually at the expense of increased memory size and increased analysis time, or by using a frequency *zoom* technique, where the entire resolution of a given analyzer or processor (such as, 400, 500, 800 or 1,000 lines) is concentrated in a selected frequency interval. As the effective filtering or analysis window is made narrower, the total processing time required becomes longer. One advantage of this approach is that virtually any signal-to-noise improvement is possible if a sufficiently narrow window can be created. A potential disadvantage is that only one frequency region at a time can thus be examined and the narrower the *zoom* window becomes, the more discrete step intervals must be examined to cover a specified frequency range.

In the standard 500-line spectrum display of the example there is an indication of a primary periodicity in the region of 290 Hz with no evidence of any other harmonics or periodicities. However, having some prior knowledge of the signals being investigated, it is obvious that there must be third harmonic information out in the region of 900 Hz. In

the figure below, a frequency *zoom* was used (100 Hz window centered at 900 Hz). The existence of two tones is now seen clearly at 863 and 897 Hz. Whereas, these harmonics were initially 10 dB below the background noise level after processing, the signal-to-noise ratio has now been improved to nominally +3 dB after *zoom*. The increased signal-to-noise ratio is seen even more clearly on the linear amplitude display shown below.



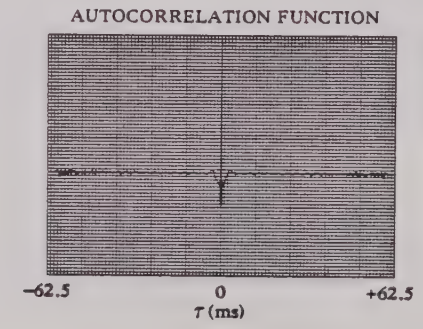
Although a 100 Hz translated range is displayed, in this case the total processing range during *zoom* was 140 Hz wide. Since the original frequency range processed was from 0 to 4000 Hz, this represents a bandwidth reduction, by using *zoom*, of approximately 28:1. Theoretically, the maximum signal-to-noise enhancement which should be achievable with this type bandwidth reduction is 14 dB. The apparent signal-to-noise improvement achieved in the given example was nominally 13 dB, or close to the theoretical optimum.

CORRELATION ANALYSIS

Effect of time difference on periodicities

Just as a spectrum analysis can give a direct determination of the amplitude and frequency content in a given signal, a correlation analysis can give a direct indication of how periodicities in a signal behave with respect to time difference. Formerly, correlation techniques were used quite extensively as a means for detecting signals in noise and "cleaning up" otherwise noisy signals, such as encountered in radar returns. There are actually many types of correlation function analysis, usually a variation of cross-correlation.

The simplest type of correlation is autocorrelation analysis in which a data signal is correlated against itself. The figure below shows the autocorrelation function of the test signal being analyzed.



The display range shown here is from −62.5 to +62.5 milliseconds with zero time delay shown at the center of the graph. Note the symmetry of the correlation function, a characteristic of autocorrelation analysis. The primary feature of the display in this case is the obvious excellent correlation at zero time delay, but with no apparent periodicities seen. The steepness of the decay at the center of the display, falling through zero in less

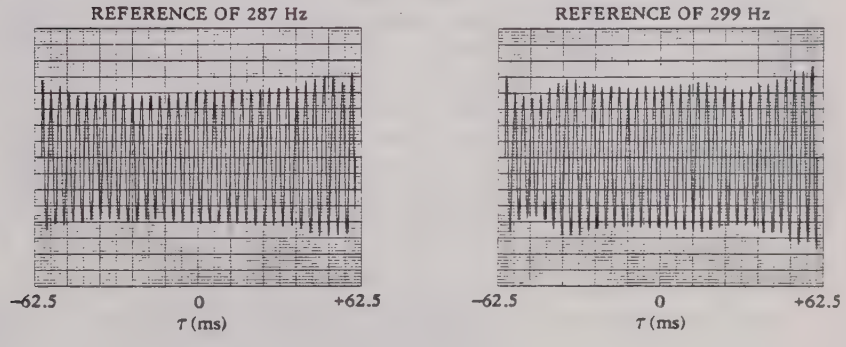
than 1 millisecond, indicates a fairly broad input spectrum. The absence of any continuous functions which appear periodic as time delay is increased in either direction indicates that within some nominal dynamic range, no periodicities appear to exist. However, since it is known that periodic signals do, in fact, exist in this data, it is obvious that a different type of correlation processing will have to be performed if effective signal-to-noise enhancement is to be achieved.

CROSS-CORRELATION WITH A PERIODIC REFERENCE

Amplitude-sensitive recovery of data signals

One of the theorems of cross-correlation analysis is that the only expected result from an averaged cross-correlation analysis is something which was common to both signals being correlated. If one of the signals being used is a periodic function free from noise, then the resulting cross-correlogram must either be a periodic signal free from noise or a function which averages to zero. If the reference signal being correlated against a complex data signal is a sine wave, the resulting correlation function will be a sinusoidal type wave of some arbitrary phase at the origin, if the frequency of the reference sine wave is contained within the complex data signal.

If another type of periodic waveform, such as a square wave, is used as the reference input and a complex periodic waveform of the same frequency is present in the data signal under analysis, it is necessary to have a good understanding of correlation functions to be able to properly interpret the resulting periodic correlogram. The data signal of the example consisted of three components; a square wave at 287 Hz, another at 299 Hz and a shaped broadband noise component. The figure below shows the result of correlating the data signal with a reference sine wave of 287 Hz. Note that a clean periodicity is recovered and that precisely 35 cycles of the waveform are seen. In this display, the average time difference between peaks is 3.9 ms, indicating a periodicity of 287 Hz. The same data signal was then correlated against a sine wave of 299 Hz. The resulting correlogram is seen below.



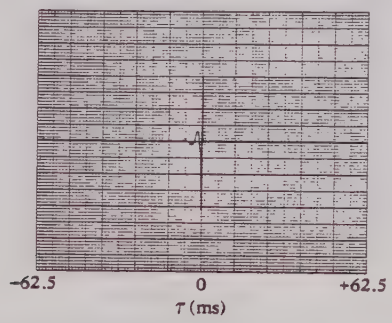
Note that in this case exactly 36 periods of the waveform are recovered, with a time difference between peaks of 3.34 ms. Other sinusoidal frequencies corresponding to harmonics of the fundamental rate can also be used in this application, resulting in an amplitude-sensitive recovery of any data signals occurring at precisely the harmonic frequency. Note that if a square wave were used as the reference input, the recovered periodicities would not be sinusoidal, but rather represent the correlation function of a square wave since there was, in fact, a square wave at the two fundamental frequencies present in the data signal. The resulting correlogram would then appear triangular.

Periodicities as unwanted data components

There may also be cases when the true data signal of interest is actually the broadband random component and the periodicities represent unwanted data components. In this case, the periodicities can, in general, be removed by correlating against a broadband

random reference signal. The figure below shows just this situation where the reference signal was the broadband noise prior to bandpass filtering. This was used as Input B to the processor with the composite data signal (representing a system output) applied to Input A. Note the complete absence of periodicities in the correlogram. Note, also, that the resulting correlogram appears as a time-reversed impulse response for the bandpass filter used. This is to be expected since the two data signals were reversed from their normal input sequence. Although in this case the application might be the removal of periodic components, the analysis also points out the ease with which system impulse response functions can be measured using broadband excitation even if periodic data is also present.

System impulse response functions



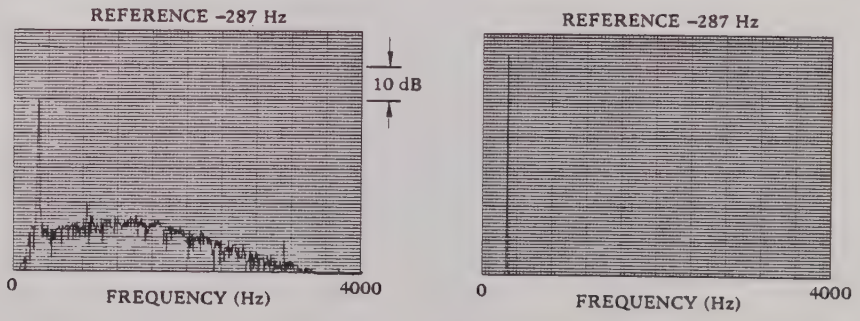
CROSS-SPECTRUM PROCESSING

Cross-spectrum analysis by classic definition involves the processing of two data signals to determine their mutual properties in the frequency domain. Since the cross-spectrum is calculated by forming the product between two Fourier transforms, by its very nature it is an extremely sensitive measurement. Because of this, it can be used in several ways as a signal-enhancement tool.

Determining existence and amplitude of periodics

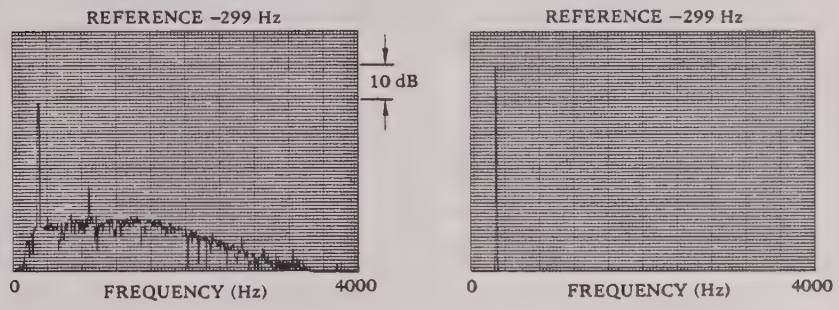
Where it is of primary interest to determine the existence, relative amplitude and, possibly, exact amplitude of periodic signals surrounded by noise, the cross-spectrum can be formed between a data signal and itself. This is equivalent to calculating the power spectrum, but will often give an increased sensitivity to periodic tones when compared with a standard voltage spectrum analysis. The squaring operation of the power spectrum tends to "multiply up" periodic signals which might be slightly higher than the background noise (after spectrum processing) and "multiply down" normally low level noise components. Usually, up to 3 dB signal-to-noise improvement can be expected by using this multiplication or squaring technique. However, where specific tones of interest are involved, the cross-spectrum can be formed between a composite signal and a sinusoidal reference input in the same fashion that cross-correlation was previously performed. The figure below shows the cross-spectrum between the total test signal and a pure 287 Hz tone.

Specific tones of interest



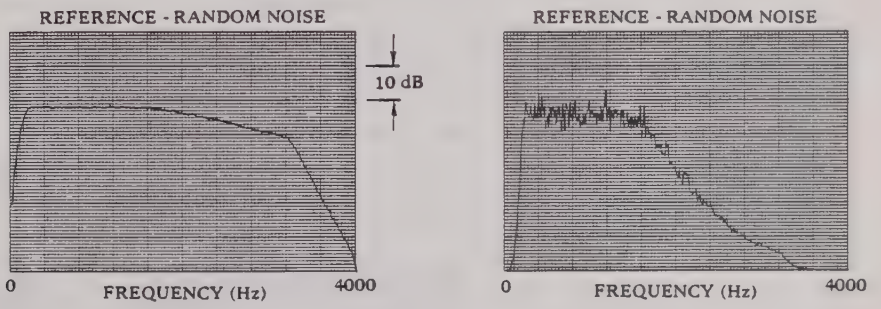
While in this case the reference signal was derived from the same 287 Hz source which is contained in the overall data, it is sometimes possible to establish a reference sinusoidal signal from a completely independent source based partially on the stability of the signal that is to be enhanced. The cross-spectrum result is shown here in both linear and log amplitude. Note in this figure and in all subsequent spectrum figures how much more clearly signals of interest are seen using linear spectrum amplitudes.

A similar test was then performed using as a reference input a fixed amplitude sinusoid at 299 Hz, again, derived from the same source as the periodic signal at that frequency obtained in the overall data signal. Note that in each case the effects of the other periodic component only 1.5 cells (1.5Δf) away from the reference sinusoidal input has been completely eliminated. This shows that the cross-spectrum as a signal-to-noise enhancement tool is extremely selective. Note also that the level of the signal recovered at 287 Hz is approximately 6% higher than that recovered at 299 Hz which, again, is consistent with the individual levels of the signal components.



Unwanted periodics

Using random noise as the reference signal input produces the figures below. As in the case of cross-correlation with the reference random signal, all evidence of periodicities has disappeared. When using cross-spectrum processing in this manner as a signal-to-noise enhancement device, it must be kept in mind that the level of the resulting cross-spectrum is greatly affected by the level of each signal input being used in the cross-spectrum process.

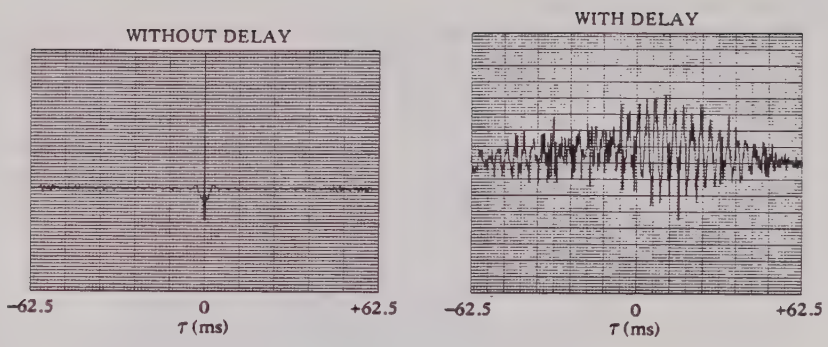


ENHANCEMENT THROUGH SIGNAL DELAY

Establishing the existence of periodicities with no prior knowledge and no reference signal

In one of the previous displays showing the correlation function of a signal which was predominantly random noise, it was noted that the correlogram consisted almost exclusively of the large spike at zero time delay. This is so because random noise correlates perfectly with itself at that one instant in time when there is no delay between the signal and its delayed replica; however, the correlation factor drops off very rapidly to zero for even a small amount of delay time. Since periodic signals have correlation factors which repeat over and over again, we have an important clue as to another potential signal-to-noise enhancement approach.

If a signal which consists of both periodic and random components were to be delayed with respect to itself and then processed for its correlation function, the preprocessing delay would tend to uncorrelate the random components of the signal, but only serve to introduce a phase shift to any periodic components. The amount of phase shift would depend on the sampling rate employed and the actual data frequency, but be of little consequence, since neither the nature of the periodicity, nor the time for one period to occur, would be changed. The use of this approach on the data signal of the example is seen in the figure which follows.



The first figure is a repetition of one previously seen and shows simply the correlation of the composite signal with itself with the characteristic large correlation factor at zero time delay. No evidence of periodicities is seen.

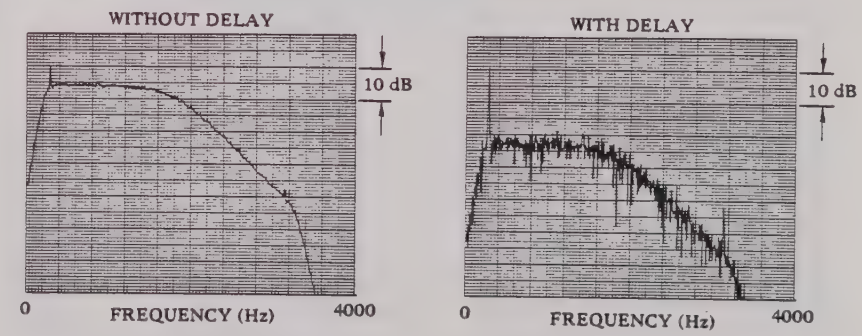
The same signal was then processed with respect to itself, but 62.5 ms of delay (1/2 memory period) was inserted in one path of the signal prior to computation. The effect this has on the resulting process is immediately obvious. The large data spike at zero time delay has completely disappeared and, now, the nature of the periodicity is seen clearly emerging.

Naturally, one of the primary purposes of this type processing is to establish the very existence of periodicities in the otherwise random signal and, clearly, this is done quite adequately. One of the key points to keep in mind for this type of processing is that it requires absolutely no prior knowledge about the data signals being processed. No reference signal is employed and the same single-channel input signal is merely processed through both input channels.

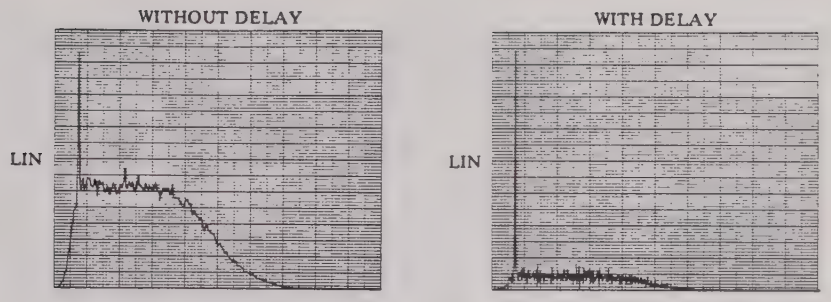
CROSS-SPECTRUM PROCESSING WITH DELAY

Enhancing periodicities by artificial delay

The same concept of introducing an artificial delay into one path of a signal process can also be used in the frequency domain using the cross-spectrum. Whereas, during correlation processing, the artificial delay in one signal path tended to uncorrelate random signals while enhancing periodic data, in the frequency domain the delay factor will again tend to enhance periodicities while giving cross products which average to very low values. The figures below show the results of the cross-spectrum process with and without signal delay.



In the original cross-spectrum display, only a single fundamental component with one harmonic at 3130 Hz was visible above the noise. With delay, these two tones are now visible clearly above the noise and, once again, it is obvious that the linear amplitude display is optimum for signal detection applications. In the spectrum case, the total signal-to-noise improvement achieved simply by using the delay technique with no other reference inputs, was 16 dB. Signal-to-noise improvement in this mode depends upon the nature of the noise and periodicities, but, in general, can vary from an improvement of 3 dB to an improvement of nominally 20 dB.



TIME-DOMAIN AVERAGING

Complete recovery of a periodic waveform and all its harmonics

There are many applications in which a repetitive signal is either generated (radar transmission) or simply exists by the nature of the mechanism being analyzed (rotating machinery applications). If it is desired to recover a periodic function and its harmonics from a composite signal which may include noise plus other periodic, but non-related, components, there are several good frequency-domain techniques. However, if a reference signal is also available which occurs in synchronism with the desired periodicity, an additional optimum technique can be used. This technique, synchronous averaging, is also sometimes called signal averaging or time-domain averaging. In practice, time-domain averaging is nothing more than synchronous sampling and, then, data summation.

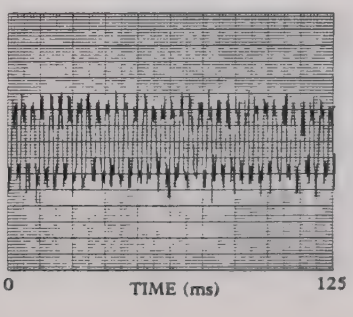
The loading of data into the input memory is started in synchronism with a reference periodic pulse. When the memory is filled, the data is transferred to an accumulating memory. The input memory with the occurrence of the next sync pulse begins to load once again. After the input memory is filled the second time, its contents are summed with the first memory load in the accumulating memory. In this manner, any components which are synchronous in time with the reference sync pulse will tend to add up at whatever memory location they occupy. Other non-synchronous signals which are either random or periodic will average down and approach zero as a limit. By processing with this technique in the time domain, an entire periodic waveform can be recovered with the lowest frequency of the periodicity equal to the reference sync frequency and with all the harmonics of that signal also retained.

Although signal averaging is a form of digital sampling, it is identical mathematically to forming the cross-correlation product between the arbitrary data signal and a sequence of unit impulses occurring at the sync rate. It represents virtually the only known technique for recovering completely a periodic waveform with all its harmonics intact. The figure below shows the periodicity of the 287 Hz square wave recovered from the composite signal seen previously. For this type of processing, the signal-to-noise enhancement which can be achieved is directly proportional to the square root of the amount of averaging time. Thus, for signal averaging, the following relationship holds.

$$S/N_{enh} = 20 \log_{10}(n)^{1/2} \text{ dB}$$

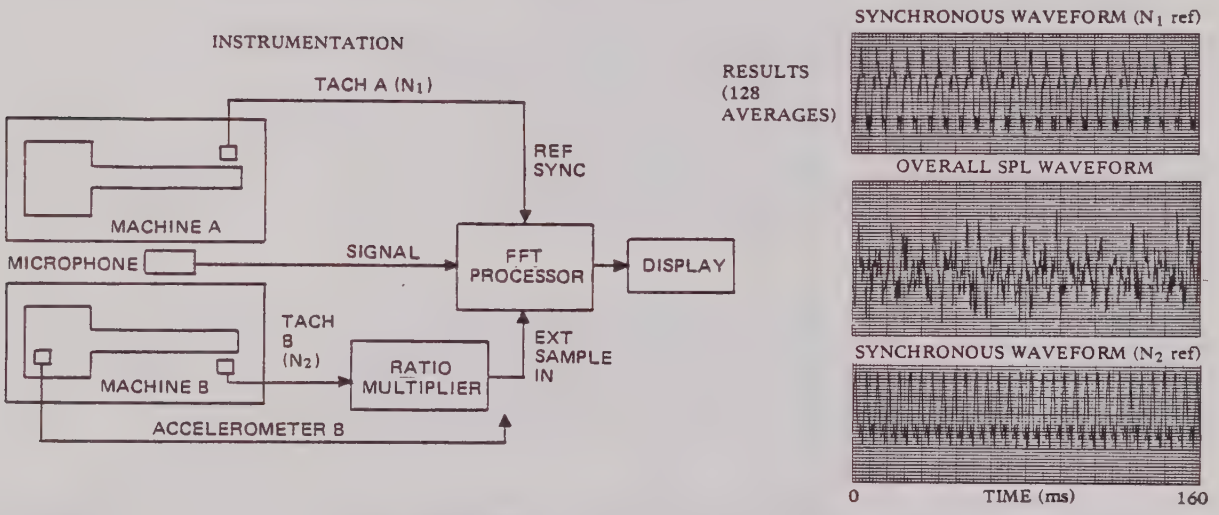
$$= 10 \log_{10} n$$

where n is the number of independent ensembles averaged.



Isolating specific noise sources

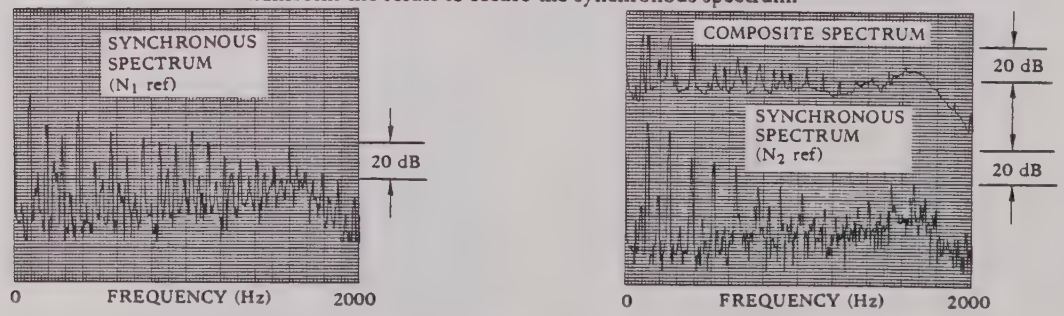
An ideal application for time-domain or synchronous averaging is to isolate specific vibration or noise characteristics associated with the operation of rotating machinery. This technique can be very effective; for example where several large machines are operating in the same area and it is necessary to isolate the machine which is the source of a dynamic characteristic. The instrumentation below was used to observe the time waveform and extract from the overall sound pressure level waveform the component of this waveform associated first with N_1 operation and then with N_2 operation. When performing a signal averaging process, an external sync signal must be supplied as a reference to formulate the correct average. Signal averaging can then be done using the external sync input and internal sampling. If it is necessary to track changing speed characteristics, external synchronization with external sampling can be employed.



SYNCHRONOUS SPECTRA

Eliminating unrelated harmonics

After time-domain averaging, it is often extremely useful to Fourier transform the time-averaged result. Spectrum averaging is not necessary since synchronous time-domain averaging has already been performed. Both the overall standard spectrum and synchronous spectrum associated with the machine operation seen previously are shown below. The fundamental shaft speed of the two machines nearest the microphone was 5640 rpm (94 Hz) and 7440 rpm (124 Hz). The contribution of these two terms with their harmonics and broadband noise components to the composite spectrum is seen in the figure below. The two synchronous spectra have effectively eliminated the effects of these harmonic components generated by the non-referenced machine and, in addition, have reduced broadband noise contributions by an average of greater than 40 dB, revealing the presence of many harmonic components previously masked. If an external sync or tach pulse is available, one of the best possible signal-to-noise enhancement procedures is to synchronously time average a raw data waveform and then Fourier transform the result to secure the synchronous spectrum.



STANDARD AND SYNCHRONOUS SPECTRA REFERENCED TO N_1 AND N_2

PRIME SPECTRA

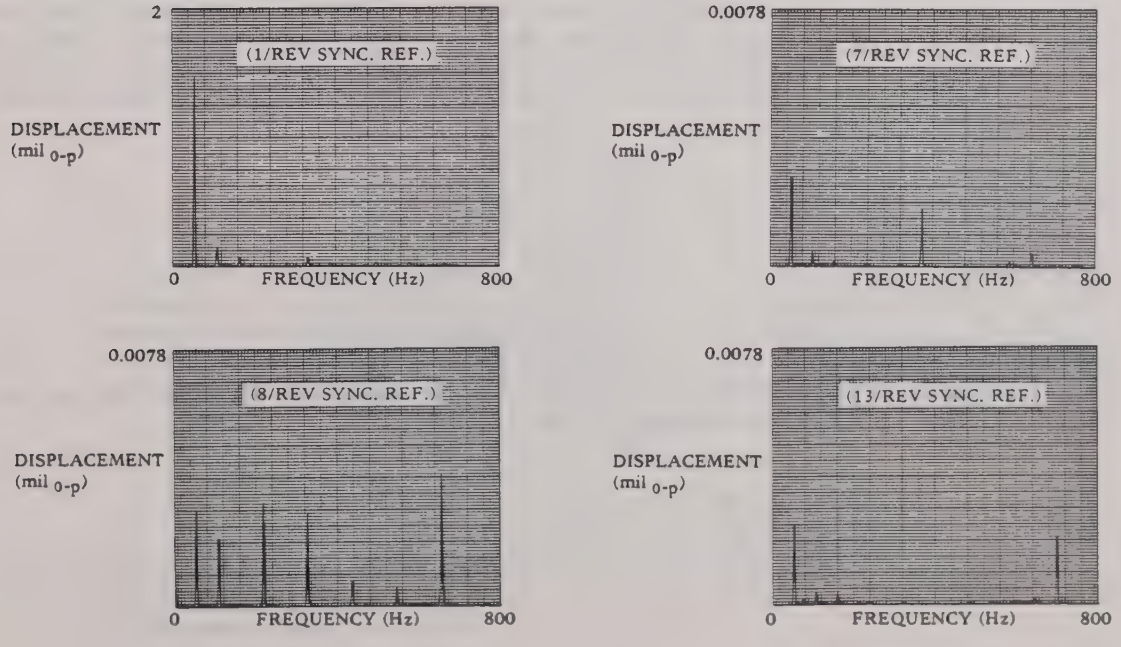
Enhancing a specific harmonic

The previous section showed that using a fundamental tach pulse the computation of synchronous spectra can provide a powerful signal-processing tool. Interesting characteristics are obtained if some manipulation of a 1/rev tach pulse is performed prior to synchronous spectrum computation. The use of the synchronous spectrum with a fundamental or once-per-rev tach reference produces a spectrum which, in effect, has the characteristics of a *comb filter* in which the teeth of the comb are spaced at multiples of their fundamental tach rate. If the one-per-rev tach signal is multiplied by a constant prior to synchronous spectrum averaging, each of the teeth of the resulting comb filter shifts in accordance with the new sync reference. If the multiplication factor is such that it corresponds with a harmonic of the signal being analyzed, that specific harmonic will tend to be greatly enhanced.

Effects of multiplication by prime, and not prime, constants

In a synchronous displacement spectrum taken using a 1/rev reference tach signal, and a noncontacting eddy current probe mounted in a gas turbine, it is obvious that the predominant components seen reflect a large unbalance situation with little higher order harmonic content. Multiplying the tach signal by 7 and then using it as the reference sync input produces a synchronous spectrum in which the 7th harmonic has been significantly enhanced. The fundamental signal is still present, but the harmonics between the fundamental and 7th have been significantly reduced on a relative basis (also representing a gain of 256 from the original scaling). If, on the other hand, the tach signal is multiplied by a constant which is not a prime number, submultiples of the multiplier will also contribute to the resulting synchronous spectrum. A tach multiplier of 8 was used to generate a reference sync signal. Not only was the 8th harmonic enhanced, but also the second, fourth, etc. As a final example of synchronous spectra, the tach signal was multiplied by 13 and clearly the 13th harmonic of running speed is the primary component which has thus been enhanced. Although the relatively high level of the fundamental signal still shows up in this resulting spectrum, it is obvious that other harmonics between the fundamental and 13 have, in effect, been discarded as the 13th harmonic has been enhanced, a classical example of a prime spectrum.

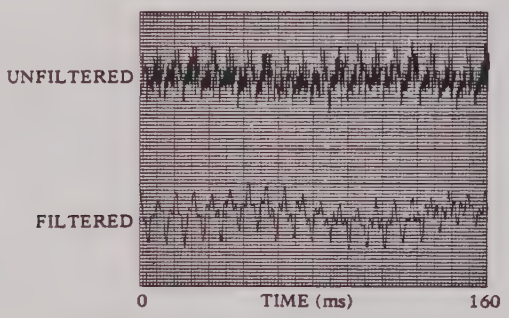
SYNCHRONOUS SPECTRA



DATA FILTERING

Isolating signal characteristics

In many cases, an important characteristic of a signal may be masked by some unwanted repetitive or broadband random signal. If the characteristics of the portions of the signal which are wanted are distinct enough from the unwanted, a simple filtering process can be used to isolate the desired signal characteristic. This process could be either high pass, low pass or bandpass filtering such that the filtered signal can then be observed or processed in either the time or frequency domain. An example of this is seen below, in which a condenser microphone was used to monitor the noise produced by an operating, motor-driven fan where there was also broadband wind noise present. Applying a low pass filter, a simple act, has isolated the predominant time domain characteristic, a noise signal dominated by the fundamental and second harmonic of the machine operating speed. Naturally, adjustable filtering could be used in this case to select a specific portion of the signal's spectrum and observe its characteristic in either the time or frequency domain.



UNFILTERED AND LOW PASS FILTERED SOUND SIGNAL

DIGITAL FILTERING

Optimizing signal filtering

In the preceding section, it was seen that using a low pass or bandpass filter can often enhance a signal to the extent that the information which can be obtained from the signal is greatly increased and the signal can be much more clearly visualized. There are many cases where a signal is available in sampled value form and where a certain type of signal cleanup would be extremely valuable in interpreting time-domain signal representation. In many of these cases, it would be desirable to optimize a signal filtering or signal processing task to the actual data signal. In these situations, a digital filtering technique offers an optimum processing condition in terms of defining the filter shape, stability and accuracy of the filtering process, and convenience both in changing filter characteristic and in observing the resulting filtered waveform. Conceptually, digital filtering is equivalent to observing an output waveform which is the convolution product of an input signal to be filtered and the impulse response of the filter to be implemented, represented by

$$o(t) = \int_0^T f(\tau)\ h(t-\tau)\, d\tau$$

where $o(t)$ is the resulting filtered or convolved waveform, $f(t)$ is the signal to be filtered and $h(t)$ is the impulse response of the filter characteristic.

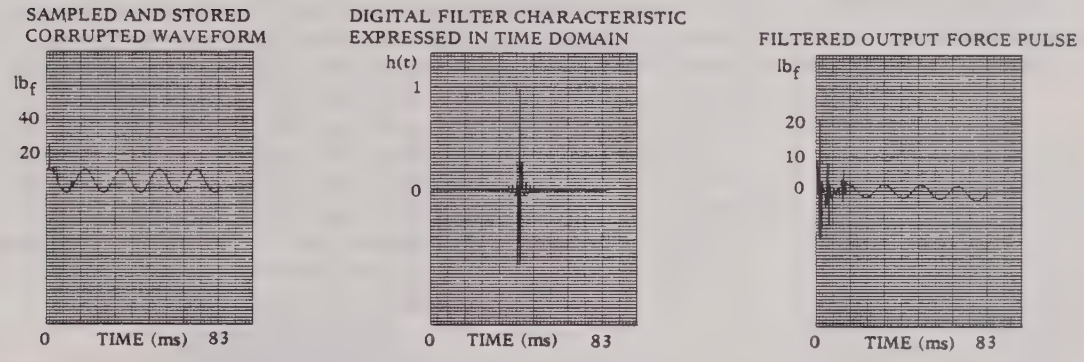
In digital-processing terms, a linear digital filter can be defined using the principle of super-position as follows;

$$y(nT) = \sum_{m=o}^{n} h(mT)\ X(nT - mT)$$

where $x(nT)$ is the input signal; $h(mT)$ defines the filter weights; $y(nT)$ represents the output sequence; and T is the sampling interval.

Eliminating unwanted tonals

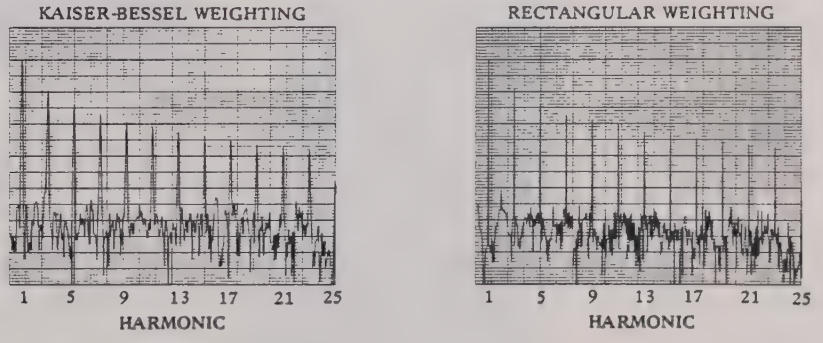
An example of a signal requiring some extensive cleanup in order to assist interpretation of a physical phenomena is given in the figure below. Here an impact waveform was recorded, but was heavily corrupted and virtually obliterated by the presence of an unwanted tonal. A filter shape in the frequency domain was then specified to eliminate the tonal, but optimize the characteristic of the impact spectrum. The equivalent specification of this filter in the time domain is seen below. The resulting filtered waveform which has significantly reduced the effects of the periodicity within the time frame of the pulse itself is given below. Here, not only the initial impact, but also the characteristics of some of the rebounds previously masked by the periodicity are now clearly seen. In terms of signal cleanup, especially where data signals have been previously sampled or available in digital form, the concept of digital filtering is extremely useful.



WEIGHTING CONSIDERATIONS

External sampling and rectangular weighting for optimizing signal-to-noise enhancement

The effective filter shape which is achieved when doing a spectrum analysis using a sampling type of system is either partially or exclusively determined by the type of windowing function employed in the analysis. Selection of a window alters the selectivity characteristic of the Fourier transform process and, as a result, can affect signal-to-noise enhancement considerations. Many weighting functions exhibit nulls in their side-lobe characteristics at appreciable amplitude levels, producing an effective filter shape which is perfectly rectangular at the frequency cells (Δf) of the nulls. The most obvious example of this type characteristic is the rectangular weighting window. In most cases, the rectangular window cannot be employed because of the unwanted truncation and side-lobe effects which it produces. However, if an external sampling input, synchronous to a periodic signal input, is available, rectangular weighting can be used to give an extremely selective analysis characteristic. An example of this is seen in the figures below.



The first figure is that of a synchronous spectrum analysis performed up to the 25th harmonic, using external sampling inputs to an FFT processor with Kaiser-Bessel weighting. Excellent signal-to-noise enhancement is achieved; however, although the Kaiser-Bessel window has nearly an optimum filter shape, its actual filter characteristic is clearly visible.

In the next figure, the same analysis is performed using rectangular weighting. Note the extremely sharp filter shape, and also a slight apparent improvement in signal-to-noise ratio over the previous condition. In situations which permit external sampling, especially where synchronous averaging will not be used, this can be an important factor to consider in optimizing signal-to-noise enhancement.

ENHANCEMENT BY THREE-DIMENSIONAL DISPLAYS

Detection of buried periodics which are changing in frequency with time

One of the most difficult signal-to-noise enhancement tasks is the detection of periodic signals nearly buried by a random background when the periodic signals are moving about in frequency as time passes. A pure-tone signal moving about in this random background will often be missed if it is merely observed on a real-time oscilloscope display. For these applications, especially when no synchronizing or reference signal is available, averaging techniques are often inappropriate inasmuch as they would tend to smear the very signal that is under observation into the background noise. Sometimes, a display in terms of a *waterfall* (moving spectrum history) is most appropriate. The real-time spectrum of a signal, which consists predominantly of random noise, is also a very random display. However, visual enhancement can be achieved by displaying spectra of this nature in a continuous three-dimensional presentation. The figure below shows a typical presentation of this type in which a tone is swept back and forth through a predominantly random background. In this case, no spectrum averaging was performed as it is important to know precisely the total excursion in frequency of the signal being observed. It would be extremely difficult, if not impossible, to extrapolate the total signal excursion characteristic in this instance if using only a standard oscilloscope display.

OVERLAP PROCESSING WITH VISUAL ENHANCEMENT

Obtaining faster visual presentations

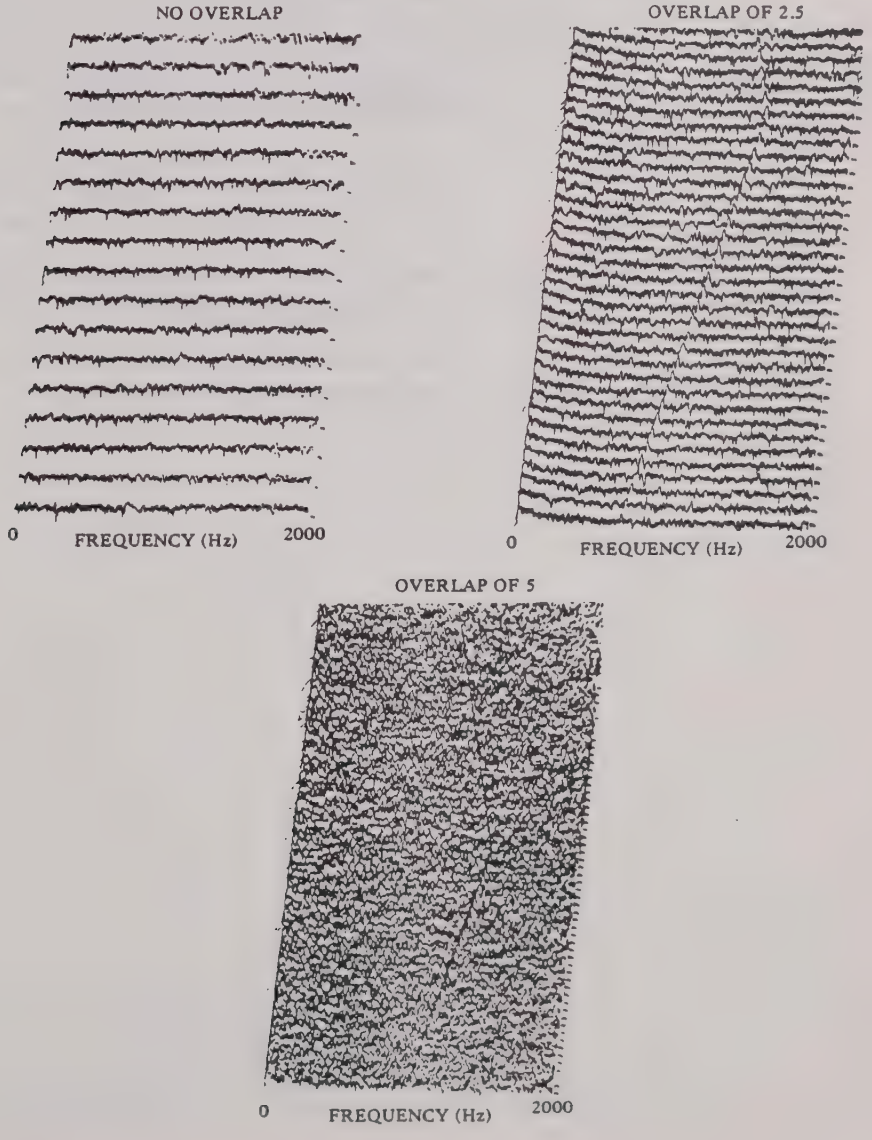
In addition to observing a three-dimensional presentation of amplitude, frequency and time, enhancement is also available through the use of overlap processing. In this context, overlap processing is defined as the ability to produce a spectrum display in a period of time faster than the time samples were originally accumulated under the condition of continuous accumulation and updating. For example, if 4 transforms per memory period are used, the processor will perform 4 transforms in a 1 memory period time frame rather than just one transform. Initially a block of data is read from input memory to processor memory and a transform is performed. One-fourth memory period later another complete block of data is read from input memory to processor memory and a transform is performed. However, the second block of data contains three-fourths of the data collected in the first block plus one-fourth of new data. This is overlap processing. By its very nature, overlap processing is not, in general, designed to increase statistical confidence of a resulting analysis, but if it is done correctly, can give some spectrum averaging still within the time frame of 1 memory-load period. However, one of the

primary advantages and applications of overlap processing is to obtain faster visual presentations of exactly what is happening and, as in the example, additional visual signal enhancement.

Determining precise signal excursion

The figure below shows a spectrum scan from 0 to 2000 Hz in which a 500-line analysis was performed with no overlap or redundant processing. Each spectrum display represents one non-redundant spectrum scan in which a totally new memory sample was employed each time. Contained within this background noise spectrum is a sinusoidal signal at an rms level of −17.5 dB with respect to the rms level of the noise which was moving across the spectrum at a rate of 42 Hz per second. No evidence of this moving tone can be seen in the first display.

The next display shows the identical signal condition, but with an overlap factor of 2.5:1. The same analysis range of 2 kHz and the same effective bandwidth filter was used in both cases, but the number of spectrum displays per unit time has been increased by a factor of 2.5. An obvious periodicity is now apparent in the spectrum.



Finally, an overlap factor of 5 was employed. This is, once again, shown by the increase of number of displays per unit time. Again the signal stands out quite clearly and even though no averaging has been employed, sufficient signal-to-noise enhancement is achieved to permit an accurate determination of precise signal excursion. Previous investigations have shown that the overlap factor cannot be increased indefinitely. Typically, for this type of display, optimum overlap-processing factors range between 2 and 8, with no appreciable increase in apparent visual enhancement using more overlaps.

CONCLUSIONS

1. Signal enhancement can be achieved in the time and frequency domains.

2. For straight spectrum processing, signal-to-noise enhancement improves as the analysis filter bandwidth decreases.

3. For correlation processing, signal-to-noise enhancement relates to the square root of total averaging time.

4. If no reference or synchronizing signal is available, single-channel data signal enhancement can be achieved using two-channel signal processing techniques with an adjustable artificial delay between data signals.

5. If it is desired to recover periodic signals from noise, and a reference or synchronizing signal is available, there is maximum signal-to-noise enhancement in either the frequency or time domain by using synchronous averaging.

6. Overlap processing can effectively be used to achieve visual enhancement and, in some conditions, actual signal-to-noise improvement through averaging.

7. Three-dimensional displays, where available, can significantly improve signal-to-noise conditions from a signal-detection standpoint.

DSP-021
7-78

AUTOMATIC SIGNAL GENERATION

JULY 1978

Scientific-Atlanta
Spectral Dynamics Division

United States: P.O. Box 23575 • San Diego, CA 92123-0575 • (619) 268-7100 • TWX 910-335-2022
Europe: Horton Manor • Stanwell Road • Horton, Slough, SL3 9PA, England • Telephone: Colnbrook 3211 • Telex: 849406

AUTOMATIC SIGNAL GENERATION FOR SYSTEM STIMULUS

IDEAL ANALYSIS CONDITIONS

For the general case of measuring system dynamic response to a system stimulus of either random, swept sine, transient or fast chirp nature, the narrowest possible effective filter bandwidth is desirable. This condition occurs whenever a signal to be processed is periodic and, not only periodic, but "periodic within the window." That is, containing an exact integer number of cycles within a data block which is being processed. If this occurs, then a rectangular window can be employed, since truncation effects are then not possible and need not be of concern. Unfortunately, in the general case, these periodic, transient or random signals will almost certainly not be perfectly periodic within the data block length. In that case, a weighting window of some nature must be employed to avoid truncation effects and the window will be specifically designed to achieve optimum dynamic range together with the narrowest possible effective filter shape.

PERIODIC SIGNAL

Not Periodic In The Window

Since the rectangular window contains, theoretically, the narrowest possible effective filter shape, under the right conditions it is often attractive to attempt to use this window in an analysis or testing situation. However, unless conditions are just right, the rectangular window may destroy the very analysis which is being attempted. Figure 1 shows the analysis of a periodic signal which was not periodic in the window and was processed using a rectangular window.

Periodic In The Window

Figure 2 shows the same type of signal processed with a rectangular window, however, under conditions such that the signal was perfectly periodic in the window. Now, lower level harmonics are clearly visible and the analysis dynamic range has virtually doubled. From a practical testing standpoint, obviously a periodic signal cannot be swept across a pre-selected frequency range using an unweighted analysis since there will be many, many frequencies where truncation will occur, giving rise to spurious contributions.

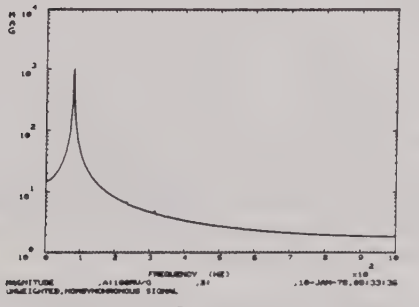


Figure 1.

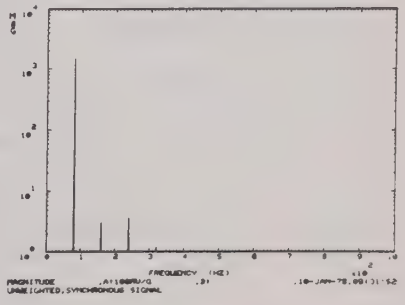


Figure 2.

SYNCHRONOUS SIGNAL GENERATION

Time Waveform

Nevertheless, a signal can be derived covering a broad frequency range and yet of such a nature that no truncation terms will be present, thus permitting rectangular weighting. This signal would be required to contain an excitation component at each frequency resolution element to assure practically continuous coverage over the selected frequency region. If a series of frequency components situated precisely in the middle of each frequency cell is inverse transformed, the resulting signal meets this criteria. If this is done, cell by cell,

across the selected frequency range , and the resulting phase of each synthesized periodic component is randomized, a waveform is produced such as Figure 3. Although appearing perfectly random, this signal is actually synchronous in time and repeats precisely frame after frame.

Signal Spectrum

The spectrum magnitude within each cell is identical from cell 1 to cell 400 producing an extremely flat spectrum as seen in Figure 4. This spectrum plot was done on an unweighted basis and shows the extremely sharp cutoff of the signal spectrum with the spectrum components reduced by more than 60 dB within one frequency resolution element. In actual practice, this signal represents an additional, continuous output from the Model SD360 which is clocked synchronously over the selected frequency range of operation. By providing outputs from cell 1 to 400, the spectrum output, for example, covers the region 2 Hz to 800 Hz when the 1 kHz range is selected and 0.2 Hz to 80 Hz if the 100 Hz range is chosen. The implementation of this concept is "synchronous signal generation" (SSG).

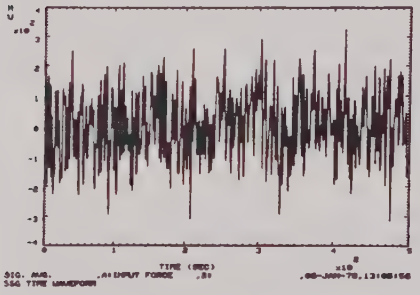


Figure 3.

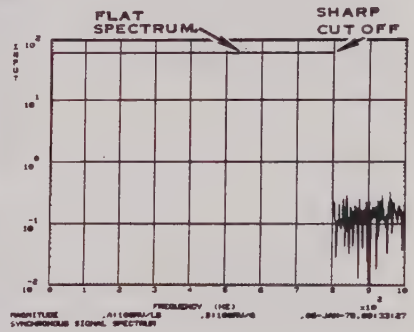


Figure 4.

APPLICATION OF THE SSG SIGNALS TO REAL STRUCTURES

SSG Excitation

If the synchronous signal is applied to a dynamic structure with fairly linear behavior, an unweighted analysis can be made of both the excitation and response since perfectly synchronous signals are involved. In fact, since the signal represents perfectly stationary and virtually periodic waveforms, a measured frequency response function will often tend to converge instantaneously without the need for averaging. An example of this is given in Figure 5 where a structural transfer function was computed using a single frame of unweighted excitation and response, and the synchronous signal generation concept. Note the extremely smooth transfer function, both in terms of magnitude and phase, and the sharp peak which describes the resonance at 315 Hz.

Broadband Random Noise Excitation

Exciting the same system with broadband random noise, then measuring the weighted transfer function based on one ensemble of excitation and response produces Figure 6. Although the general shape of the transfer function, both in terms of magnitude and phase, is quite apparent, the measurement of precise values would obviously require some additional averaging to be performed. Note that for the general signal excitation case (non-synchronous source), some type of weighting or windowing must be employed. Although this will assist in providing a valid transfer function measurement and cause the measured result to converge more rapidly to the true answer, the use of a symmetrical weighting function can also have an undesirable broadening effect during the measurement of high Q responses and limit to some extent the total effective measured dynamic range.

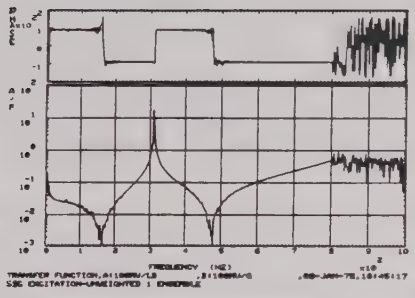


Figure 5.

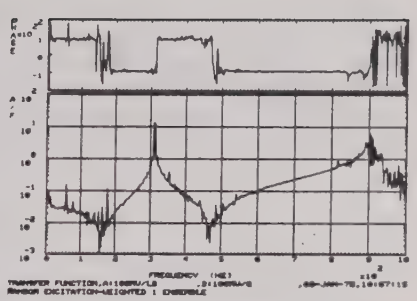


Figure 6.

Comparison of Results

An example of an optimum application of the SSG excitation technique to a dynamic structure is seen in Figure 7. Here, the synchronous signal was applied to a mechanical system and the ratio of response acceleration to input force measured using the average of 64 ensembles. This was done with rectangular weighting with an apparent dynamic range of the transfer function slightly in excess of 80 dB and an extremely sharp definition of the resonant peak at 315 Hz.

The same transfer function, measured using broadband random excitation (non-synchronous) and the weighted average of 64 ensembles, is shown in Figure 8. Although an extremely smooth transfer function is once again achieved, note that the peak definition is not nearly as sharp, giving an apparent measured dynamic range to the transfer function of slightly over 70 dB.

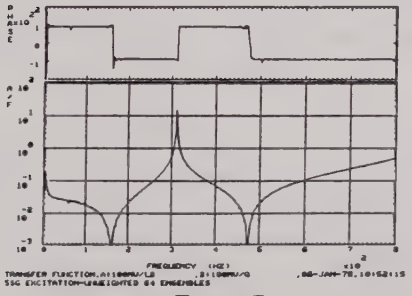


Figure 7.

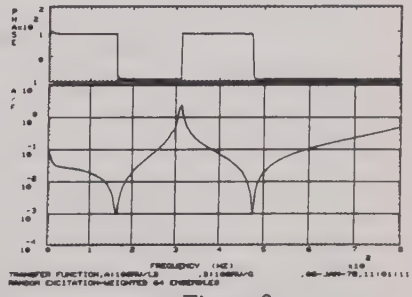


Figure 8.

THE EFFECTS OF SYSTEM NON-LINEARITY

In some structural test configurations, the system whose frequency response function is to be measured may exhibit severe non-linear characteristics. For example, this is often the case when dealing with elastomeric mounting materials and many types of damping systems. Since the SSG waveform actually appears as a periodic forcing function, the relative level of the excitation signal does not vary with time as it would using "pure" random excitation, Thus, non-linear effects do not tend to average out. Therefore, transfer function distortions do not smooth out as one might normally expect under these conditions, so that it may be necessary to revert to a normal random type excitation.

Using Rectangular Weighting

Three examples of non-linear system response to different excitations are given in Figures 9–11. The first shows a response for a system with non-linearity, excited using SSG inputs. Rectangular weighting which was seen to be optimum for linear systems was employed and 64 ensembles averaged. No reduction in variance was noted using averaging and the results are difficult to interpret and, essentially, non-satisfactory.

Using Kaiser-Bessel Weighting

Kaiser-Bessel windowing function was employed with 64 averages. The variability of the measured frequency response function is somewhat improved when compared to the unweighted case, but, once again, would not be deemed as a satisfactory result. The final example of non-linear system response was developed using broadband random excitation with a symmetrical window function and once again 64 ensembles were averaged.

Note that the phase across the entire frequency region has become acceptably smooth and that the peaks of the transfer function are now clearly discernible with a definable average response level. Thus, for many cases of apparent system non-linearity, the use of broadband random excitation will permit many different levels of response to be excited and averaged, permitting some data convergence in the desired transfer function magnitude.

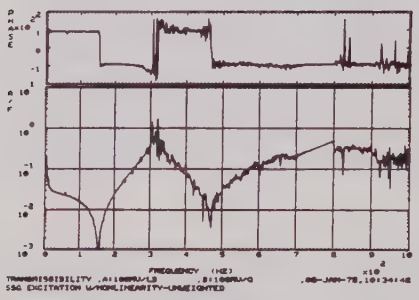


Figure 9.

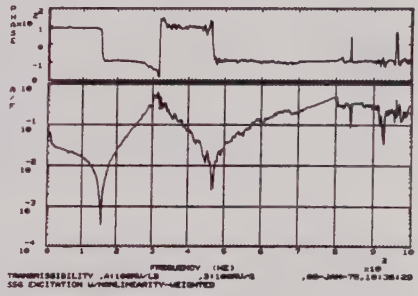


Figure 10.

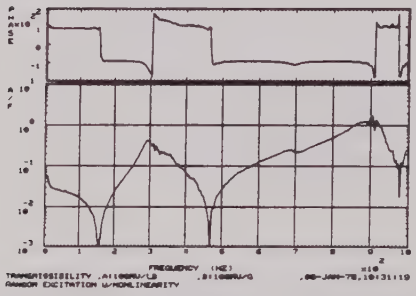


Figure 11.

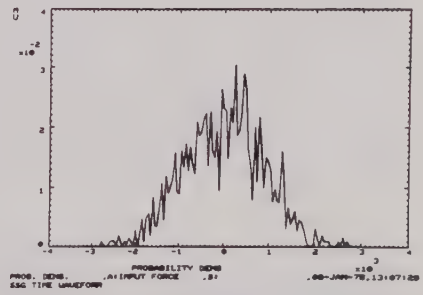


Figure 12.

SSG ADVANTAGES

Waveform Amplitude Characteristics

The time-domain characteristic of a typical random SSG signal was seen in Figure 3. The amplitude probability density characteristic of this same signal is seen in Figure 12. Since the SSG waveform is repetitious frame after frame, further averaging of the amplitude characteristic does not change the basic probability density shape. The SSG waveform obviously covers a wide range of amplitudes and, considering its unique and advantageous characteristics, does a reasonably good job of approximating a random waveform distribution.

When properly used, therefore, in the excitation of fairly linear systems, the SSG approach can provide several distinct advantages over conventional methods. These can include:

- The ability to use rectangular weighting and thus, obtain the sharpest possible filter resolution definition.
- Because of the extremely sharp effective filter shape with rectangular weighting, an improvement in signal-to-noise ratio on the order of 6 dB can usually be achieved.
- Due to the periodic nature of the SSG signal, broadband transfer functions can be measured without averaging, permitting an extremely effective speedup in the amount of structural response functions which can be measured in a given period of time.

SSG BLOCK DIAGRAM

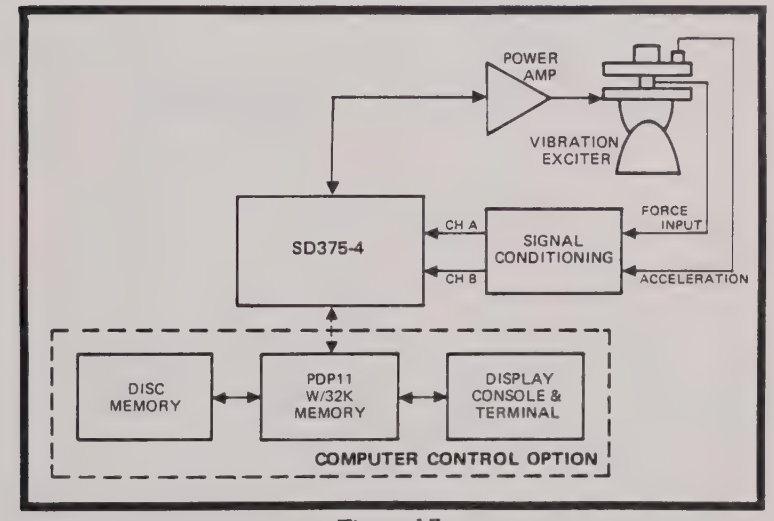


Figure 13.

The broad concept of the SSG approach is shown in Figure 13. Although the SSG option functions in a stand-alone capacity, it can also be used under computer control, such that the output frequency range can be remotely specified and changed via automatic program control.

DSP-022
6-78

OVERLAP PROCESSING

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Scientific-Atlanta
Spectral Dynamics Division

United States: P.O. Box 23575 • San Diego, CA 92123-0575 • (619) 268-7100 • TWX 910-335-2022
Europe: Horton Manor • Stanwell Road • Horton, Slough, SL3 9PA, England • Telephone: Colnbrook 3211 • Telex: 849406

EXPERIMENTAL FREQUENCY RESPONSE MEASUREMENTS

The concept of performing a structural modal analysis involves the measurement and interpretation of many, many structural frequency response functions, typically ay least one for each location which is to be included in the measured mode shapes. When using an FFT processor for measuring the frequency response functions, it is often possible to employ a variety of excitation sources and, of course, one of the tasks is to perform the desired measurement in as simple and expedient a manner as possible, but yet eliminate as many potential pitfalls as possible. But what are some of the potential pitfalls?

Some of the things of which to be aware depend on the type of excitation being used. Others are strictly potential limitations imposed by the use of an FFT processor with finite word size and finite length memories. For example, when performing tests using impact excitation, overloading the processor input on either channel must be avoided while at the same time preserving as much dynamic range of the measurement as possible by not being too conservative in attenuator settings. Similarly, when working with undamped systems and using impact excitation a high Q system response extending for a longer time duration than the block lengths being used for a given frequency range of operation should be avoided. Should a response signal extend beyond the processor's block length, serious truncation errors could result, If windowing is employed, measured signals, such as impact excitation pulses, should not be reduced through the symmetrical windowing process, thus, decreasing measurement signal-to-noise ratios.

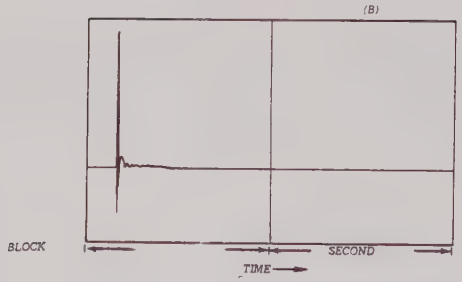
In order to get the best possible dynamic range from a measurement using impact excitation, it is desirable to allow the response signal to decay away completely. Although there is a tradeoff between total dynamic range of measurement and filter spacing or analysis resolution, it is nevertheless desirable to perform an analysis using impact excitation in such a way that the response signal can decay away to virtually zero. Anything less than that can decrease the measured dynamic range, thus making it difficult or impossible to accurately define frequency response functions, in regions of high stiffness values. For this reason, it is often necessary, especially when dealing with slightly damped structures, to process acceleration response signals over more than one "block" of data.

BLOCK VS. OVERLAP PROCESSING

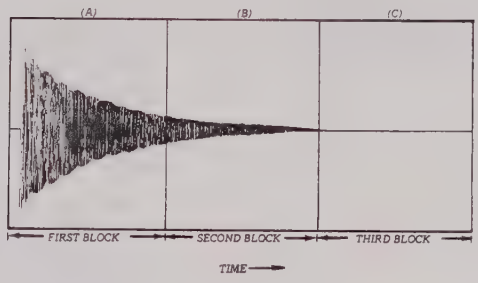
The processing time of an FFT computing device is the total amount of time required to calculate a desired parameter, such as a transfer function, once the loading of input data memory or memories has been accomplished. If the time required to process and display the results is equal to or less than the time required to sample the data signals and load input memories, the processing is said to be performed on a real time basis. If the processing can be performed significantly faster than the time required to sample and load signal inputs, it is possible to perform multiple analyses of the input signals on a segmented basis. The concept of performing a new analysis on a segment of data in which only a portion of the signal has been updated (some old data, some new data) is referred to as overlap processing. One of the principal benefits of high analysis speed or a high real time rate is that it permits overlap processing to be performed. As the following illustrations will show, the use of overlap processing offers significant advantages. Some of these advantages are:

- Gives repeatable results, test after test
- Simplifies the use of weighting functions contributing to the complete elimination of truncation effects
- Speeds up significantly the data acquisition and processing function which provides improved test results in a shorter amount of analysis time.

FORCE INPUT

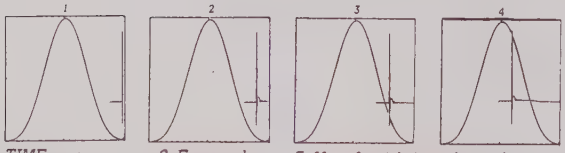


ACCELERATION RESPONSE



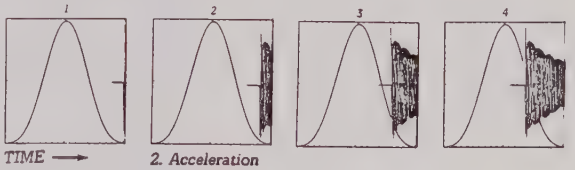
OVERLAP PROCESSING

The force and acceleration pulses travel through input memory, are smoothed by the weighting window and are processed many times.

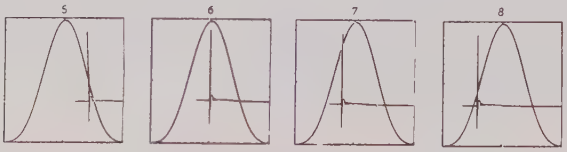


2. Force pulse first enters memory.

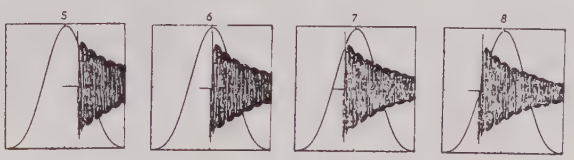
3. Use of weighting w/o overlap will seriously degrade s/n ratio in many instances.

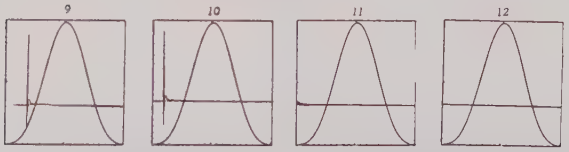


2. Acceleration response first enters memory.



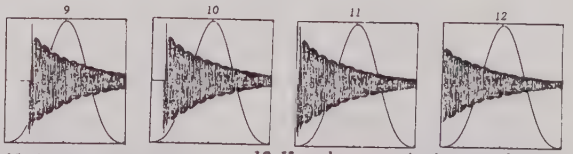
6. Optimum position of pulse in memory but cannot be guanteed w/o overlap.





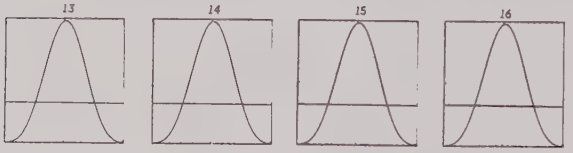
10. Pulse position in memory if transient capture used.

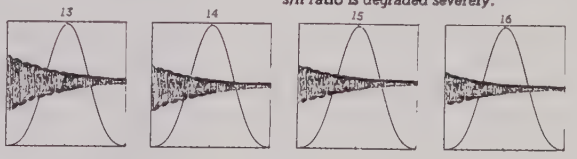
12. Force pulse has now passed through memory after many transforms were taken of it.

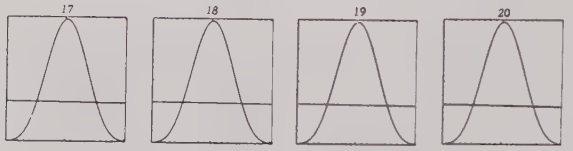


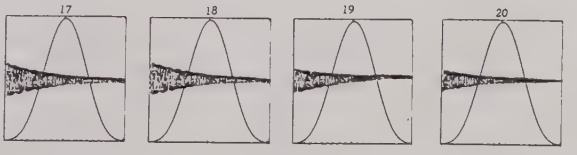
10. Acceleration response position in memory if transient capture used.

12. If overlap processing is not used, severe truncation occurs at both ends of memory without weighting. With weighting, s/n ratio is degraded severely.









IMPACT EXCITATION

Single Data Block

Processing single blocks of impact force and acceleration data shown in Figure 1 gives the measured transfer functions displayed in Figures 2-4. The data blocks correspond to the time response traces shown. By processing the blocks with no weighting characteristic added, the truncation effect on the acceleration trace produces typical scalloping of the measured frequency response. When the symmetrical weighting function is employed as in the second transfer function, the reduction in signal-to-noise level produces a frequency response function approaching that of the spectrum of a periodic wave. One of the best possible transfer function measurements based on a single block of force and response data is achieved when the data is rotated to the center of the effective block length and a symmetrical weighting function employed. This is seen in the last transfer function. However, it is obvious that a single block of data is not sufficient to correctly describe the desired frequency response function especially in the case where the acceleration response exhibits a slow decay causing it to extend beyond the block length. A more optimum technique must, therefore, be employed and is examined in the following sections.

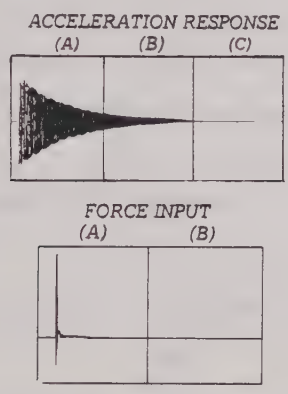


Figure 1.

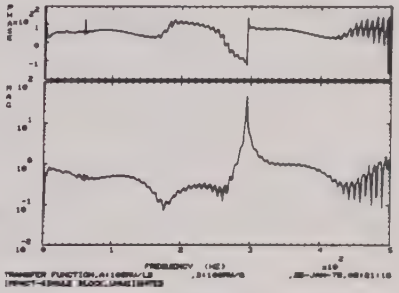


Figure 2.

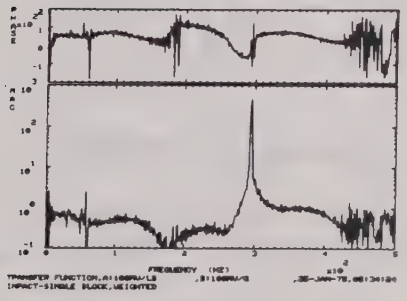


Figure 3.

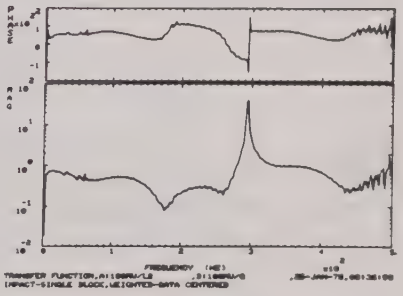


Figure 4.

SINGLE IMPACT BLOCK PROCESSING

Unweighted

The transfer functions in Figures 5–12 represent measured frequency response functions from an impact test repeated eight times. For each of these tests, the measurement block length was one second and eight blocks were averaged together to form each frequency response function. In each case a single impact was used and the unweighted eight second processing time permitted a full decay of the acceleration response. The test results are obviously not repeatable. There is approximately 20 dB variation in measured frequency response peaks. It is readily determined that the results obviously are dependent upon the relative location im memory of the initial acceleration response. Note that none of the measured transfer functions gives a smooth, acceptable result. This type of unweighted block processing is often used in strictly computer-based analysis systems.

MEASURED FREQUENCY RESPONSE FUNCTIONS

Impact Test Repeated 8 Times

Processed Results of the 8 Blocks Averaged

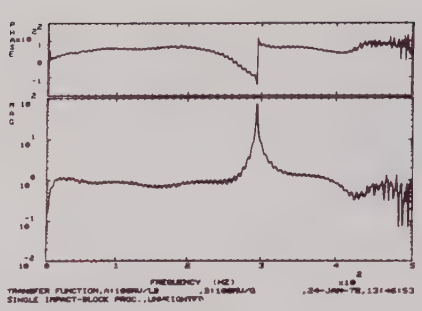


Figure 5.

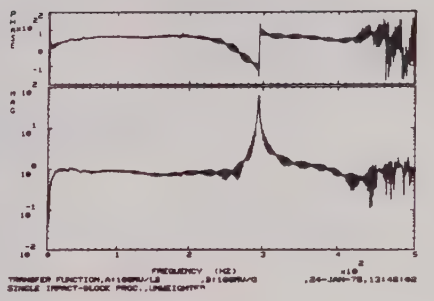


Figure 6.

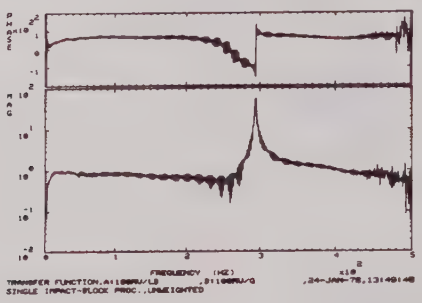


Figure 7.

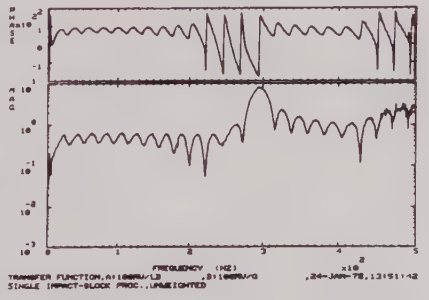
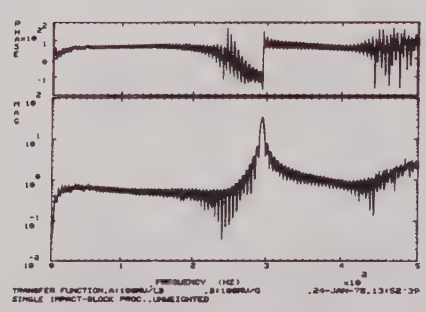


Figure 8.



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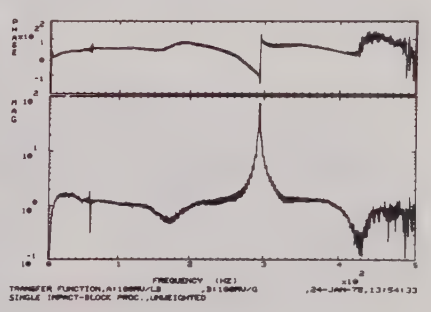

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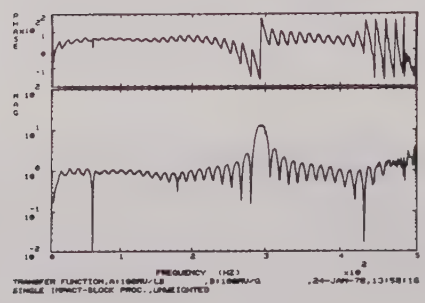

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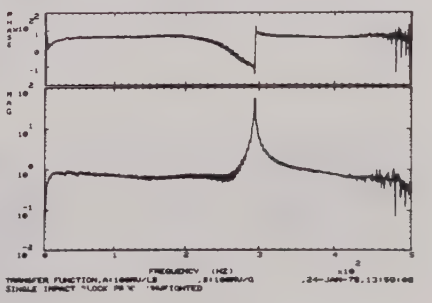


Figure 12.

SINGLE IMPACT BLOCK PROCESSING

Weighted

In an attempt to eliminate truncation effects during a single impact test, a symmetrical weighting function was used. However, weighting in conjunction with block processing resulted in eight transfer functions with variation in the measurements from nearly acceptable transfer functions in the first and third displays to a virtually unrecognizable result in the last display. Once again it is seen that the symmetrical weighting function used in conjunction with block processing is very dependent upon the precise relative location of measured signals within the memory block and that repeatable results cannot be guaranteed. The obvious lack of repeatability would, therefore, seem to eliminate block processing as a viable technique for measurement of system transfer functions when using a single impact excitation. Figures 13—21 illustrate this lack of repeatibility.

MEASURED FREQUENCY RESPONSE FUNCTIONS

Impact Test Repeated 8 Times

Processed Results of the 8 Blocks Averaged

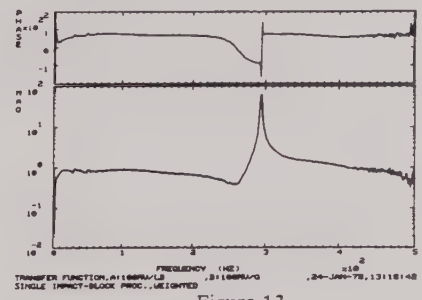


Figure 13.

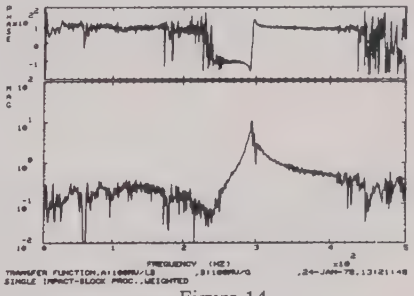


Figure 14.

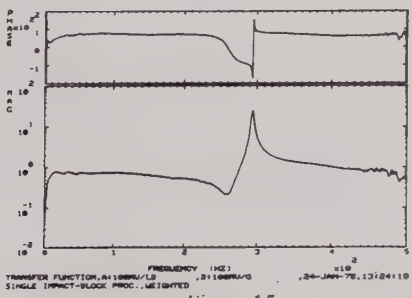
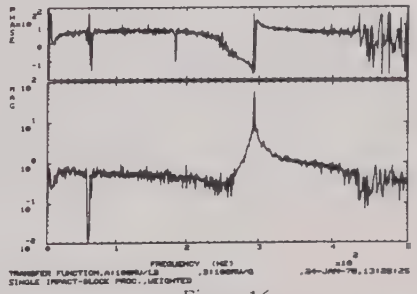


Figure 15.



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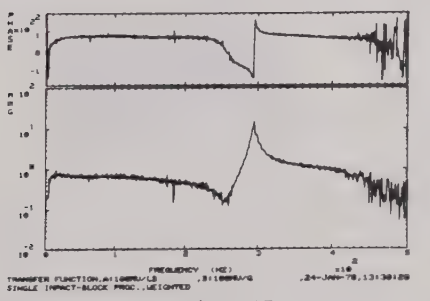
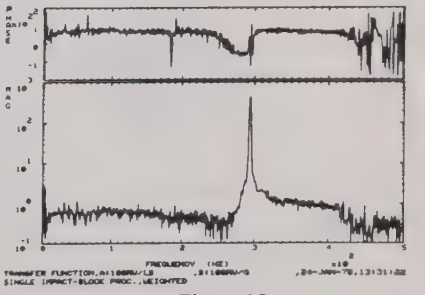


Figure 17.



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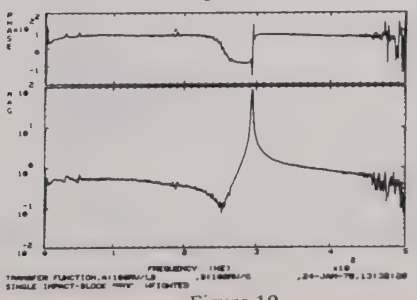

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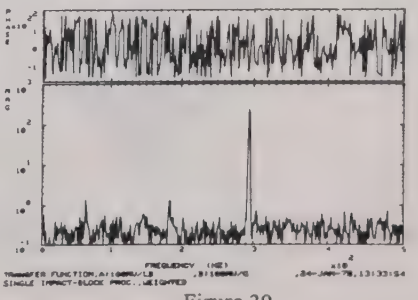


Figure 20.

SINGLE IMPACT, OVERLAP PROCESSING

Symmetrical Weighting

An optimum processing can be employed to use the entire decay associated with a single test impact, but at the same time eliminate undesired truncation effects due to finite memory length. This is the technique described previously as "overlap processing" in which many successive transforms of partially, common data blocks are taken as a signal "travels through" the processor memory. By having available the speed to perform overlap processing, the effects of signal location within a memory block are significantly reduced. At the same time, combining the processing speed with overlap permits the use of a symmetrical weighting function since the signal is guaranteed to appear at the peak of the weighting function at least part of the time during its travels through the entire processor's memory. Overlap processing with weighting gives repeatable results with consistent peak frequencies, peak magnitudes extremely repeatable and consistent phase data in the region of interest using single impact excitation. Although a single impact technique may not be the recommended test practice, it can be seen that usable results can be obtained from a single impact on almost a real time basis only if an overlap processing technique is employed. Averaging several impacts is often recommended. If several impacts are averaged using overlap processing, certainly the resulting transfer function is expected to be better than if several impacts are averaged using block processing. Overlap processing results are shown in Figures 21–28.

MEASURED FREQUENCY RESPONSE FUNCTIONS

Impact Test Repeated 8 Times

Processed Results of the 8 Blocks Averaged

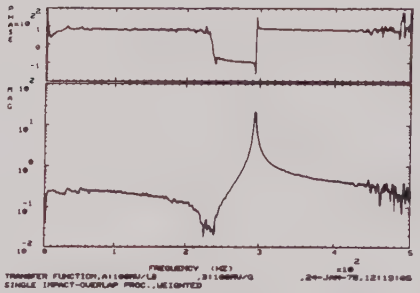


Figure 21.

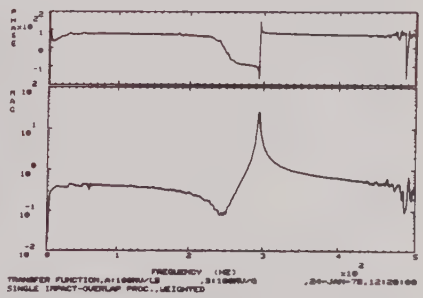


Figure 22.

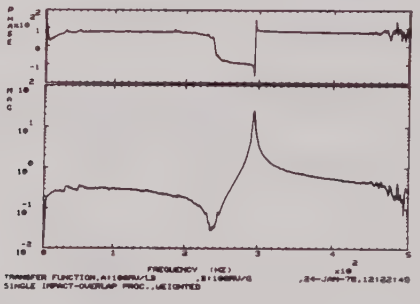


Figure 23.

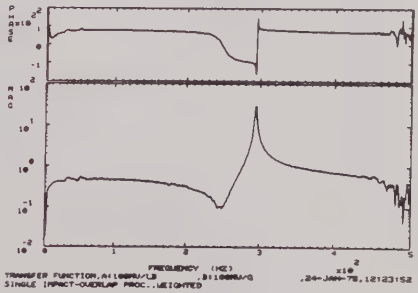


Figure 24.

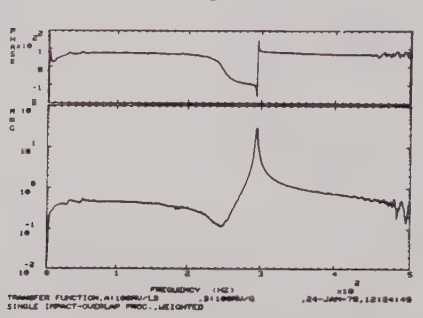


Figure 25.

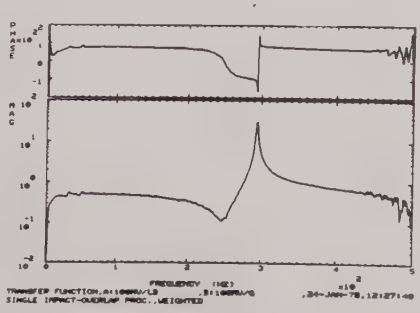


Figure 26.

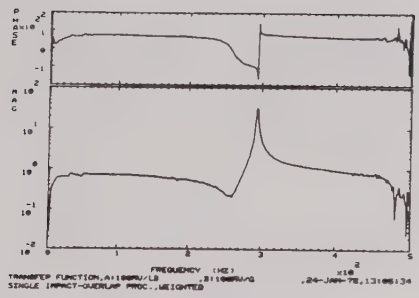


Figure 27.

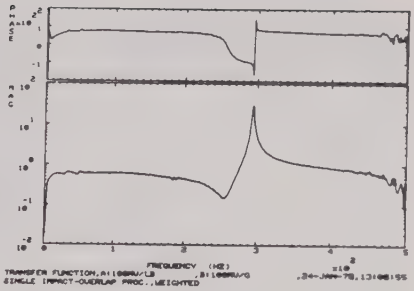


Figure 28.

SYSTEM EXCITATION

Chirp Method

One popular method of exciting a structural system is by using a fast sine sweep, also known as chirp excitation. Often the chirp is designed in such a way that the entire fast sine sweep is accomplished within one memory block or period. If this can be accomplished, then single-block processing is often used. As seen previously, however, and also in Figure 29, the loading of a full scale sine sweep at either end of system memory will cause truncation as sampling of the sine sweep signal is terminated.

To prohibit this truncation of the signal, windowing or weighting is applied to the sampled sine sweep. However, as seen in Figure 30, a specific portion of memory in this application corresponds to a specific frequency of the sweep. Thus, windowing of the data on a single-block basis can severely reduce the effective signal level over a portion of the frequency region of interest, creating very poor signal-to-noise ratio over this portion. It is, therefore, worthwhile to once again consider an optimum processing technique for working with fast sine sweep data. Figures 29-32 show a typical force input and acceleration response on both an unweighted and a weighted basis when a resonanant structure is excited.

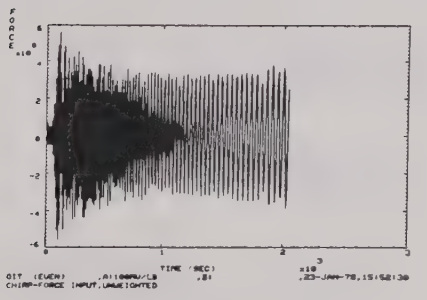


Figure 29.

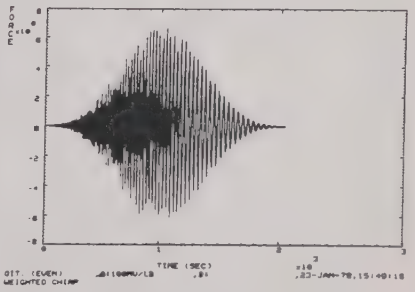


Figure 30.

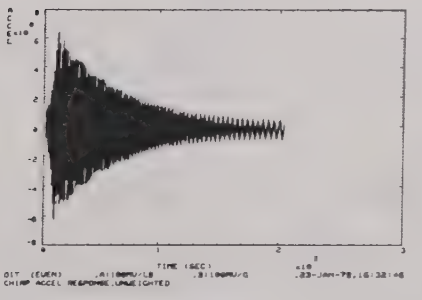


Figure 31.

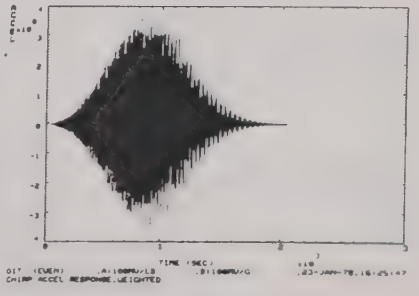


Figure 32.

CHIRP EXCITATION

Single-Block Measurement

Single-block processing for transfer function computation during chirp excitation obviously creates a problem situation, whether or not, windowing is employed. In the unweighted example shown in Figures 33 and 34, truncation effects produce many unwanted oscillations in the measured frequency response function, making it difficult to interpret the true magnitude and phase characteristics at many frequencies over the desired frequency region. On the other hand, the use of the symmetrical windowing function reduces measured force and acceleration response levels to those approaching noise level except over the middle portion of the windowing function. In the example in Figure 33, a "clean" measurement is achieved only within the region from 50 Hz to 130 Hz. One approach to achieving a more satisfactory frequency response function for the condition of chirp excitation would obviously be to process more than one block of force input and acceleration response.

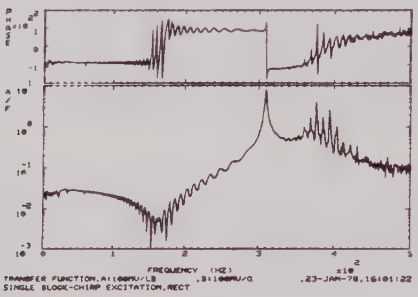


Figure 33.

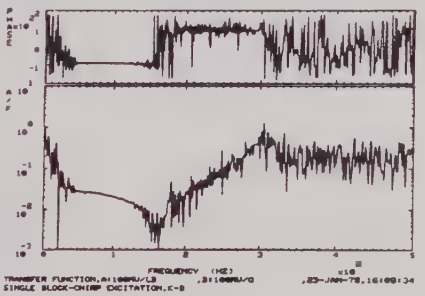


Figure 34.

CHIRP EXCITATION

Block Processing
Unweighted

8 Data Blocks Averaged

Figures 35 through 40 show a chirp excitation test repeated six times. In each case, eight blocks of data were averaged together on a block processing basis. No external weighting or windowing function was employed such that the quality of the results is obviousy influenced by the relative location of the sine sweep with respect to the end of the memory blocks. For the six experiments performed, only one appears to have achieved even a reasonable approximation to a smooth transfer function and the peak levels of the measured frequency response vary from measurement to measurement by approximately 20 dB. It is obvious that unweighted block processing for this type excitation cannot provide repeatable test results and is, therefore, and inappropriate test technique.

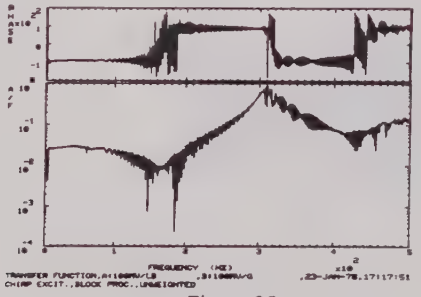


Figure 35.

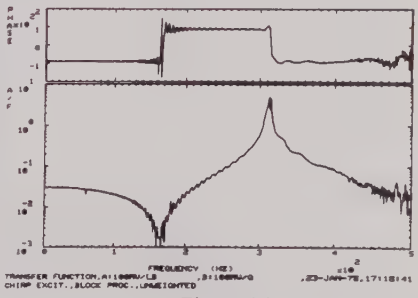


Figure 36.

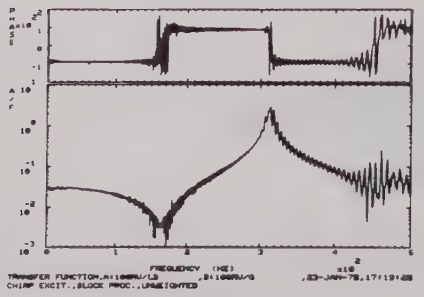


Figure 37.

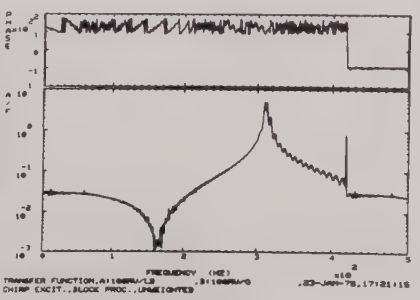


Figure 38.

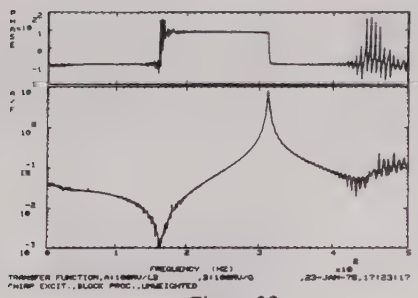


Figure 39.

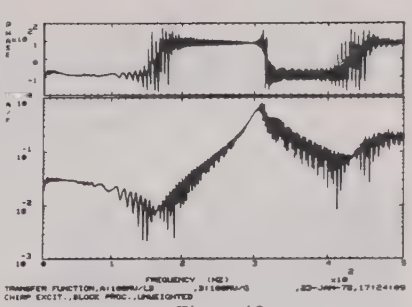


Figure 40.

CHIRP EXCITATION

Block Processing
Kaiser-Bessel Weighting

The chirp excitation test was again repeated. Once again, eight blocks of data were processed using block processing, but a Kaiser-Bessel window was applied to each data block. Although several of the measured transfer functions now appear quite smoothed, test repeatibility is non-existent with peak transfer function magnitude again varying by greater than 20 dB. Obviously, therefore, block processing is conjunction with a symmetrical windowing function is, again, an inappropriate and non-repeatable test technique.

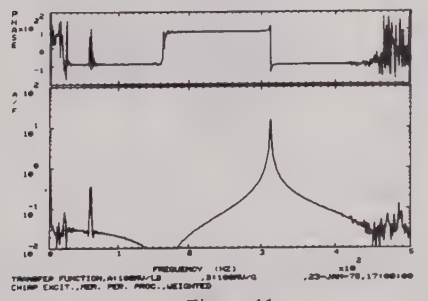


Figure 41.

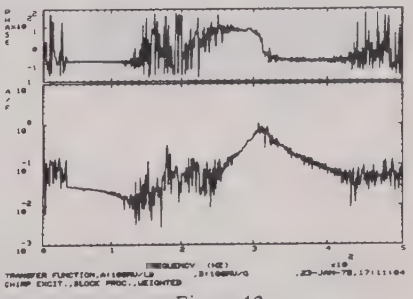
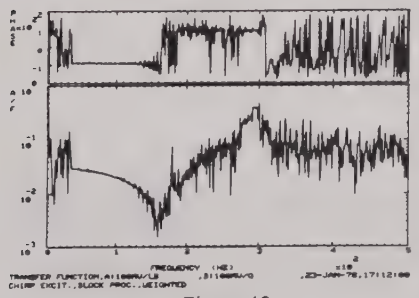


Figure 42.



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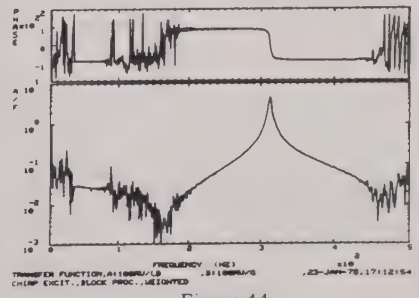
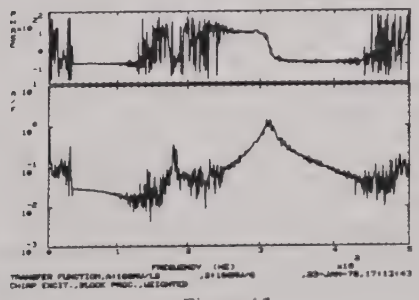


Figure 44.



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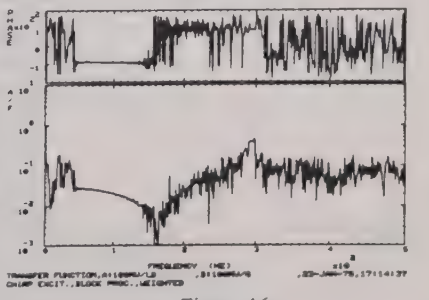
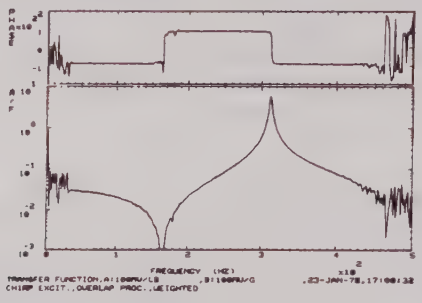


Figure 46.

CHIRP EXCITATION

Overlap Processing
Kaiser-Bessel Weighting

In Figures 47–50, the chirp excitation test was repeated four times. In this case, a symmetrical Kaiser-Bessel window function was applied to each data block and overlap processing was performed, such that each block was processed at least ten times on a continuously updating basis. The results are quite clear. Within the excitation frequency region, from 30 Hz to 430 Hz, the repeatability of a measured frequency response function at both resonant and anti-resonant frequencies is excellent. No extra precautions were taken, yet weighted, overlap processing provides measured frequency response functions repeatable in amplitude, frequencies and shape.



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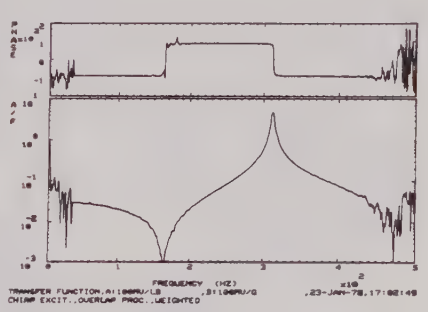

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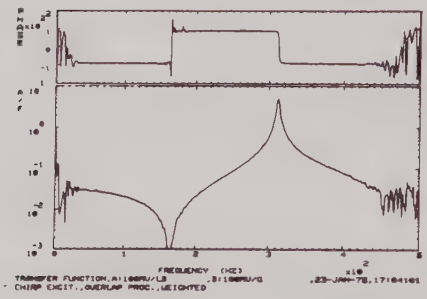

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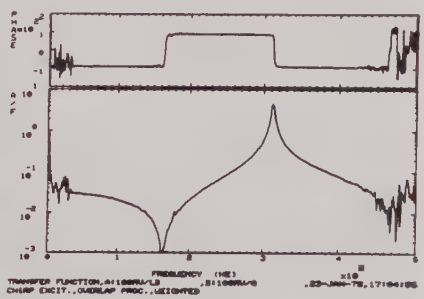


Figure 50.

BROADBAND RANDOM EXCITATION

The use of broadband random noise to excite physical structures for transfer function measurements has spread quite a bit in recent years for several reasons. If the spectrum of the noise covers the frequency range of interest, the entire frequency response region can be excited simultaneously, offering an extremely rapid way to obtain a desired frequency response function. In general, spectrum processing of random signals requires ensemble averaging in order to reduce statistical fluctuations of the measured spectrum about a true value. In FFT processors, such as the SD360, frequency response functions are typically measured by dividing the average input power spectrum into the averaged cross power spectrum between system input and output. Both the input spectrum and the cross spectrum are usually then averaged with some selected number of ensembles to reduce system statistical fluctuation. If the input spectrum and cross spectrum are measured from the same sample records or data blocks and the input and output signals are related by a linear system, then each signal has essentially the same random variation. Thus, when the transfer function is calculated, the first order effects of randomness are removed. This is usually not at all obvious, but in a practical sense it means that frequency response functions measured using random excitation converge to the true value of the transfer function far more rapidly than either the input spectrum or cross spectrum converge to their true values. In one sense this is to be expected since the transfer function, the quantity to be measured, is non-random.

Waveforms of random force and acceleration time histories are shown in Figures 51, 52, 53 and 54. Each waveform is shown in terms of a full data block, as well as expansion of the initial half of each block. Note the appearance in the acceleration waveform of modulated envelope response. For the data shown, this is caused by the high Q response of the structure being tested which tends to act as a narrowband filtering element.

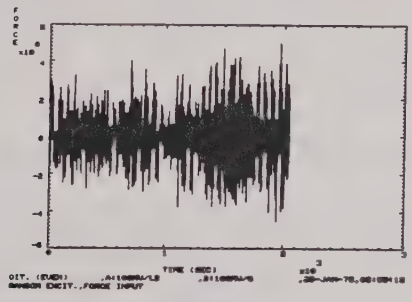


Figure 51.

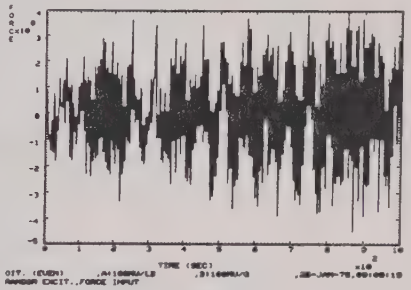


Figure 52.

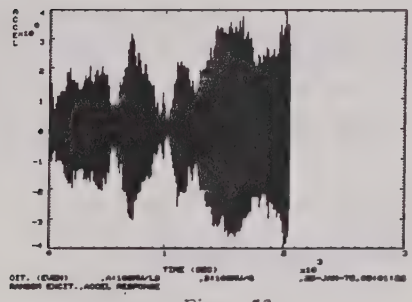


Figure 53.

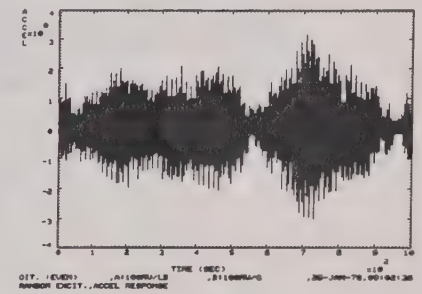


Figure 54.

The transfer function in Figure 55 was measured from a single block of random excitation and response data. A symmetrical weighting function was employed on each of the data blocks prior to the transfer function computation. A general shape of the transfer function, as well as the magnitude of the computed resonant peak, is quite good for the limited data used. It would be advantageous to employ additional averaging for this transfer function measurement.

The transfer functions of figures 56, 57 and 58 were measured using an average of successive data blocks. Figure 56 represents a four second average of signals processed in block fashion with a symmetrical weighting function and shows a fairly well behaved transfer function peak with some fluctuations in transfer function magnitude at the lower levels and in phase within several regions. Figure 57 shows an 8-second average using weighted block processing. Both the transfer function magnitude and phase show reduced fluctuations with respect to the previous 4-second average. Figure 58 shows a 4-second average using overlap processing on symmetrically weighted data blocks. In terms of smoothness in both the magnitude and phase displays, the 4-second overlap processed measurement is superior to the block-processed results for even 8 seconds of data. The use of overlap processing during random excitation thus permits faster convergence of measured frequency response functions.

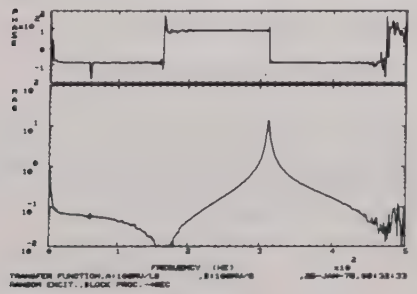


Figure 55.

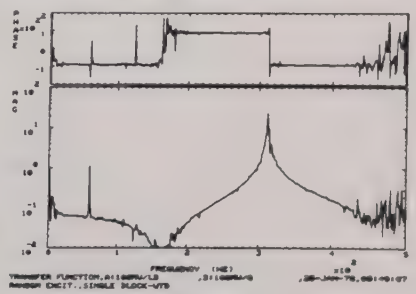


Figure 56.

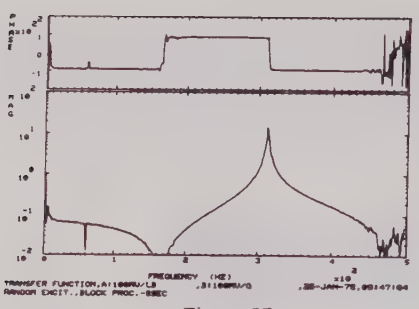


Figure 57.

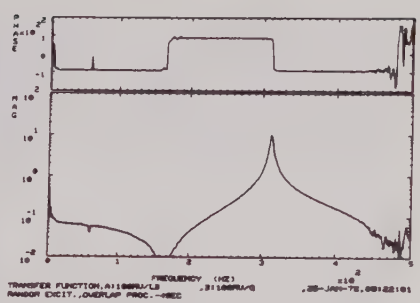


Figure 58.

The advantage of overlap processing while operating on random time function is, perhaps, seen more clearly in terms of straight spectrum processing. The final two examples, Figures 59 and 60, show a comparison between block processing of a random signal over 8 seconds of data and overlap processing of the same signal looking at only a 6.4 second sample. Note the spectrum peak at 810 Hz when overlap processing was employed. Using overlap processing, it was clear that the spectrum peak at 810 Hz was a periodic component with the largest difference value when compared with adjacent noise background. Using 8-second block processing, a plethora of apparent periodic components appear as peaks higher than the 810 Hz tone, a tone which also exhibits far greater magnitude fluctuation when processed in a block mode rather than employing an overlap processing technique.

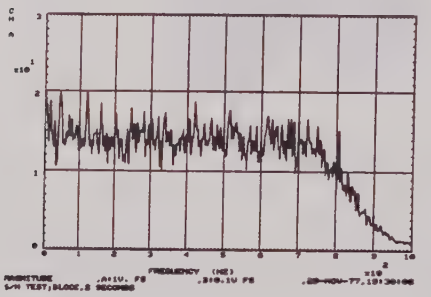


Figure 59.

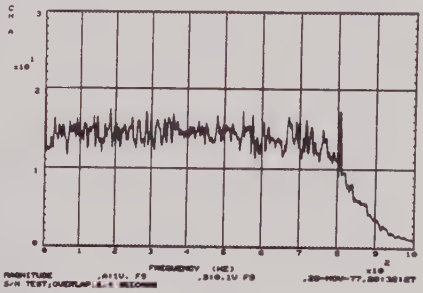


Figure 60.

CONCLUSION

The key to good transfer function measurements, when any one of a number of excitation functions may be employed, is processing speed. If a fundamentally high processing speed is available, the advantages of overlap processing can be exploited. Some of these advantages are:

- simplification in the use of symmetrical weighting functions
- repeatable test results
- faster convergence to the desired answer
- improvement in measured signal-to-noise ratios by as much as 6 dB

Since no one type of excitation function is always available or is always the most appropriate, a flexible processing system should have the capability to do overlap processing. As results have demonstrated, strictly block processing is often woefully inadequate in the important task of measuring structural frequency response functions.

DSP-035 1/80

MEASURING FREQUENCY RESPONSE FUNCTIONS ON OPERATING SYSTEMS

Scientific-Atlanta
Spectral Dynamics Division
United States: P.O. Box 23575 • San Diego, CA 92123-0575 • (619) 268-7100 • TWX 910-335-2022
Europe: Horton Manor • Stanwell Road • Horton, Slough, SL3 9PA, England • Telephone: Colnbrook 3211 • Telex: 849406

MEASURING FREQUENCY RESPONSE FUNCTIONS ON OPERATING SYSTEMS

Current availability and use of moderately priced single and dual channel analysis instrumentation has increased the understanding of low frequency dynamic characteristics. These characteristics may be those of a dynamically excited mechanical system, a biological system or a circuit measurement. In many applications including structural testing and mechanical systems development, response phenomenon have been observed without taking into account, except in a cursory way, input/output relationships, system gain or transfer function concepts. In the case of structures, the need for systems that are lighter, quieter, which rotate at higher speeds, carry more payload and fail less frequently, an increased awareness of linear system concepts and the availability of dedicated instruments to perform frequency response measurements heighten interest in frequency response measurements.

FREQUENCY RESPONSE FUNCTION MEASUREMENTS

Response measurements made at several points simultaneously often only depict the output of the system of interest. For example, at times during flight tests the only parameters available are response measurements due to the distributed loading which took place during the flight. The value of the response measurements in this case as in many cases is determined to a large extent by the characteristic of the forcing function. Figure 1 shows the response of a lightly damped structure under excitation by a random forcing function which was not controlled as to input spectrum "flatness." Although the drive signal came from a white noise generator, the interaction of the structure with the armature of the shaker created a forcing function which was anything but flat. The apparent system resonant frequencies as shown in Figure 1 are 297, 740, 1000 and 1420 Hz.

If the same measurement is made with a controlled force input using a digital random controller, the response spectrum of Figure 2 results. Here, the peaks in the response (apparent resonant frequencies) are seen to be 903, 1200 and 1510 Hz. Neither the structure nor the shaker attached to the structure has changed in any way between the two measurements shown. Only the shape of the exciting force has been varied through a careful control procedure. What does this indicate about the accuracy of the structural measurement? To obtain a better understanding of the measurement, it will be necessary to consider the concept of frequency response function measurements.

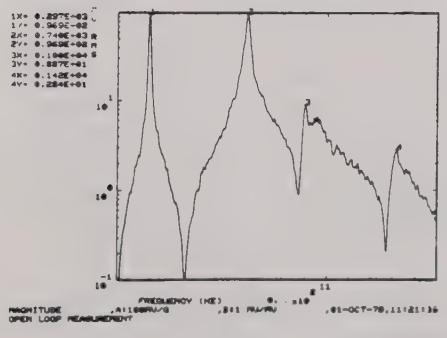


Figure 1. Response Function Uncontrolled Forcing Function

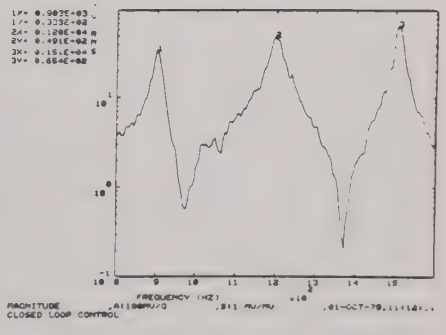


Figure 2. Response Function, Controlled Forcing Function

The measurements described and seen schematically in Figure 3 were made with a broadband random excitation. Correct frequency response function measurements, however, can be obtained using any excitation which covers the desired frequency range and provides enough system stimulus to raise the measured system response above adjacent background noise components. In most cases, adjacent background noise is considered random but nontrivial cases do exist in which periodic components are present in the measurement which must be considered noise and treated as such.

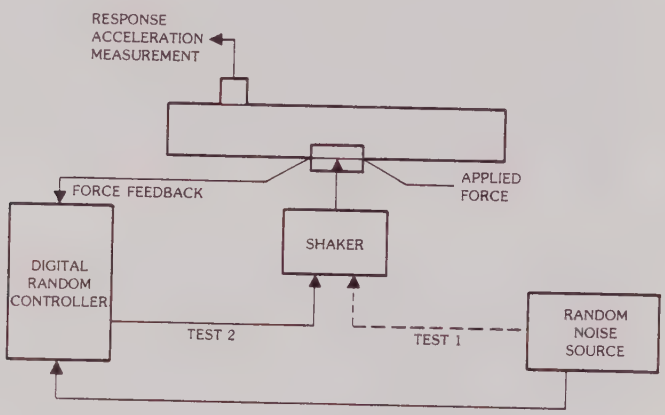
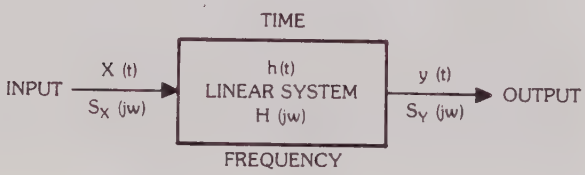


Figure 3. Measure of Structural Response Due to Random Loading

Linear System

The concept for the general case of measuring a system frequency response function (transfer function) for a linear system is shown in Figure 4.



$$H(jw) = \frac{S_Y(jw)}{S_X(jw)}$$

where:

$X(t)$ = Time domain system forcing function

$Y(t)$ = Time domain system response

$S_X(jw)$ = Fourier Transform of $X(t)$

$S_Y(jw)$ = Fourier Transform $Y(t)$

$h(t)$ = System impulse response

$H(jw)$ = System frequency response function = transfer functions in frequency domain

Figure 4. Concept for Measuring Linear System Response

Using Fourier Techniques

The two linear Fourier transforms indicated are each complex-valued functions resulting from the Fourier transform process. Thus, both S_x and S_y have real and imaginary components (CO and QUAD components) which cannot be averaged, since averaging the real and imaginary parts of the Fourier transform with a single signal will cause the average to go to zero. An averaged measured frequency response function is desired in order to obtain the smoothest possible results. Therefore, a new definition for the frequency response function as measured using digital Fourier techniques is necessary. Figure 5 is a practical definition for the frequency response function.

$$H(jw) = \frac{S_Y(jw)}{S_X(jw)} = \frac{(S_Y(jw)}{S_X(jw)} \cdot \frac{S_X^*(jw)}{S_X^*(jw)} \quad (1)$$

$$H(jw) = \frac{G_{YX}(jw)}{G_{XX}(w)} \quad (2)$$

where:

$G_{YX}(jw)$ = Cross spectrum between X (t) and Y (t).

$G_{XX}(w)$ = Power spectrum of X (t).

$S_X^*(jw)$ = Complex conjugate of $S_X(jw)$.

$$X(jw) = H(jw) \quad F(jw) \quad (3)$$

where:

$X(jw)$ = Fourier transform of system response motion.

$F(jw)$ = Fourier transform of system excitation force.

Figure 5. Frequency Response Function Definition

The ratio of the two Fourier transforms, the desired resultant, has been rationalized through multiplication by the complex conjugate of the Fourier transform of the system excitation function in Equation 1 above. This has several advantages in the physical implementation of the transfer function measurement. First, multiplication by this complex conjugate produces results which show that the desired measurement reduces to the calculation of a cross-spectrum and an input power spectrum in Equation 2. Averaging can now be performed since neither of these functions will average to zero. Secondly, the denominator of the desired fraction is the power spectrum of the input which is a real-valued quantity as a function of frequency. The power spectrum contains no phase information. This greatly simplifies the computation of the frequency response function since complex division is no longer required. Note that Equation 2 points out a very important application for cross-spectrum measurements; namely, the measurement of the phase of the frequency response function. Since the cross-spectrum is a complex-valued quantity containing both magnitude and phase information, the resulting ratio will be a complex quantity. However, since the input power spectrum is a real-valued quantity, it will normalize the cross-spectrum magnitude only. As a result, the phase of the cross-spectrum is identical to the measured phase of the frequency response function.

The resulting motion of a system can generally be described by Equation 3. The system response in the frequency domain is the product of the system frequency response function and the frequency-domain description of the system forcing function. In the more general case of structural measurements, results are not a single input/single output situation, but the response of the structure at a series of selected locations. From these response measurements, several pieces of information may be extracted. These include the amplitude and phase of motion, as well as, damping ratios and other modal parameters such as effective modal mass and effective modal stiffness. The general, multipoint structural case is more readily described in the form of a measurement matrix as seen in Figure 6.

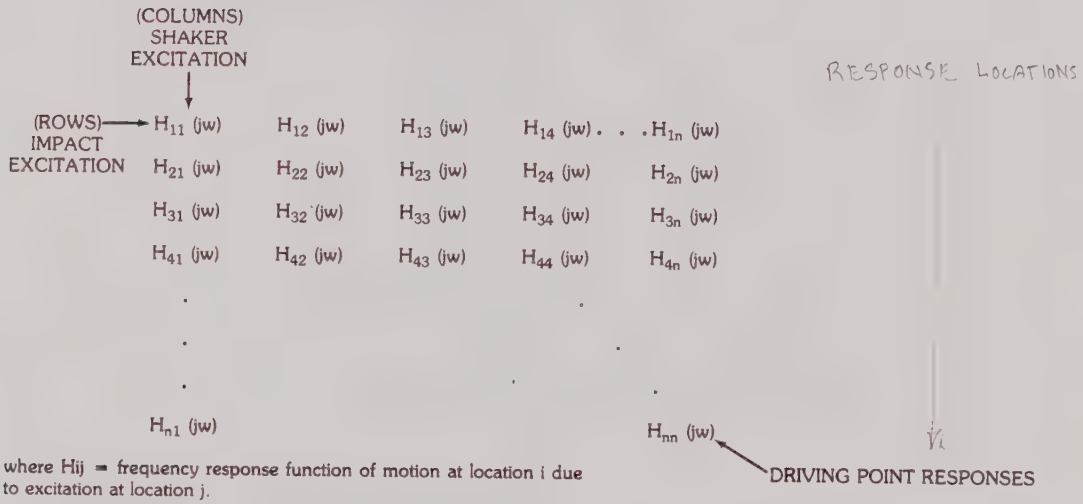

(COLUMNS)
SHAKER
EXCITATION
RESPONSE LOCATIONS
(ROWS)
IMPACT
EXCITATION
H_{11} (jw) H_{12} (jw) H_{13} (jw) H_{14} (jw) . . . H_{1n} (jw)
H_{21} (jw) H_{22} (jw) H_{23} (jw) H_{24} (jw) H_{2n} (jw)
H_{31} (jw) H_{32} (jw) H_{33} (jw) H_{34} (jw) H_{3n} (jw)
H_{41} (jw) H_{42} (jw) H_{43} (jw) H_{44} (jw) H_{4n} (jw)
H_{n1} (jw)
H_{nn} (jw)
DRIVING POINT RESPONSES
where Hij = frequency response function of motion at location i due to excitation at location j.

Figure 6. Measurement Matrix for Multipoint Structural Response

Multipoint Structural Response

Note, that if only one mode is associated with each peak in the measured frequency response function (pole in the transfer function) then the modal parameters of a structure being tested with the exception of those corresponding to components which are termed node points can be identified from any row or column of the transfer function matrix as previously described. Only one row or column of the matrix need be measured and the remaining terms are filled in by post-processing and computation, if none of the measurement points correspond to a structural node. It is interesting to note that the first row of the transfer function matrix corresponds to measuring the response of location 1 due to excitation at the various points of interest, 1 through N. In the physical sense, this corresponds to having a fixed accelerometer located at Position 1 and applying excitation to the system at each of the various locations 1 through N. Usually impact excitation is applied using a calibrated hammer with a fixed accelerometer location.

On the other hand, the first column of the matrix corresponds to measuring the structural response at Locations 1 through N while always having system excitation applied at Location 1. This corresponds to having a shaker attached to the structure at Location 1 and moving the response accelerometer from Positions 1 through N.

MEASUREMENT AND PROCESSING CONDITIONS

Regardless of the nature of the system being analyzed, several general considerations must be observed during the testing and measurement process. If artificial excitation is to be employed, care must be taken to insure that the method of excitation does indeed excite the test system over the whole frequency range of interest. At the same time, an attempt should be made to employ a level of excitation which does not drive the test system into a nonlinear or overloaded type of behavior, but does excite system responses above background noise levels. If possible, approximate actual forcing levels which the system may see in use should be used. If no external stimulus is to be applied, but the system's "self-excitation" characteristics will be used for a transfer function measurement, either a valid force measurement must be set up or two response transducers representing desirable transfer function locations carefuly established in optimal locations.

If artificial excitation is used, the type of excitation may be extremely important for a given test article. Shaker-applied random or sinusoidal excitation may be absolutely necessary for certain types of systems; whereas, pulse or impact excitation may often be more appropriate for the item to be tested. If random excitation is used, the operator has a choice among several different types of random signals which do not necessarily provide equivalent results. Three types of random signals which will be considered in this paper are:

a. Analog "pure" random noise.

b. Pseudorandom noise generated through a digital counting sequence.

c. Synchronous signal generation which is a type of pseudorandom noise with very specific and advantageous characteristics.

As mentioned earlier, many factors must be considered when making a structural transfer function measurement using artificial excitation. Of these factors, the ones that will be considered here are weighting, aliasing, averaging, coherence and synchronization. In general, certain signal processing factors such as FFT smoothing (weighting) and adequate aliasing filter protection must always be employed during a single- or dual-channel analysis. Naturally, certain exceptional conditions can exist and some of these will be noted.

Analog Noise Excitation

Although this noise as it comes from a source has a white characteristic (equal energy per unit frequency), the actual applied force can be anything but flat after its interaction with an electrodynamic exciter and structure. Figure 7, shows a driving point transfer function measured on a lightly damped structural member. The measurement combines 64 linear-averaged ensembles and produces a very acceptable frequency response measurement. Note, however that because of the extremely light system damping encountered, the resonant bandwidth of the structure being measured can actually be less than the resolution bandwidth of the processor making the measurement. If this is indeed the case, the resulting coherence function can be quite poor as illustrated in Figure 8. One way to improve the measured coherence function is to make the apparent block length of the data being processed longer, which also improves the analysis resolution with respect to the physical phenomena being measured (see Appendix A).

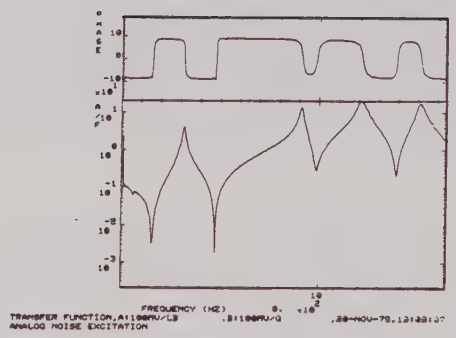


Figure 7. Driving Point Transfer Function with Phase

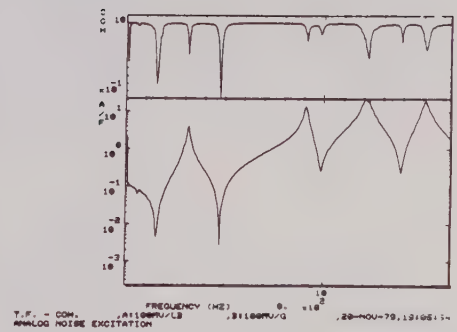


Figure 8. Driving Point Transfer Function with Coherence Function

Pseudorandom Noise Excitation

Various excitation signals have been used to measure structural transfer functions. When shaker excitation is used, signal-to-noise ratio and shaker force ratings often dictate that periodic or sinusoidal excitation be applied. However in the interest of covering as broad as possible a frequency range during one test, a multiple periodicity type of signal is often desirable. One such signal meeting this requirement is that of pseudorandom noise (PRN). This is a repetitive signal which has a random like distribution of amplitude, but which repeats itself precisely at given intervals. The length of the periodic interval is selectable and determines the periodic characteristics of the signal. The faster the repetition rate of the pseudorandom sequence, the more discrete the corresponding excitation and response spectra will become, making the excitation and response signals behave more and more like a series of equal amplitude sinewaves. Several examples of the use of this type of excitation are shown in Figures 9 through 11.

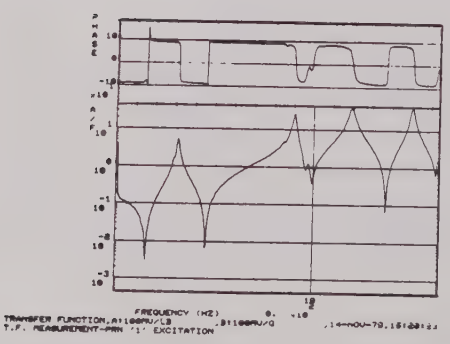


Figure 9. Measured Transfer Function PRN 1

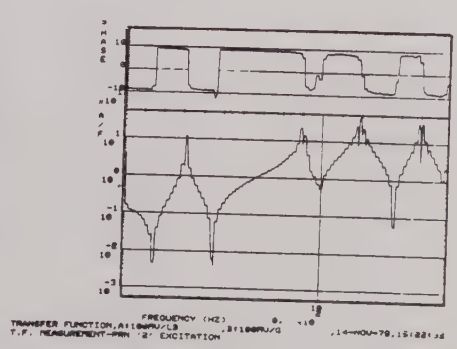


Figure 10. Measured Transfer Function PRN 2

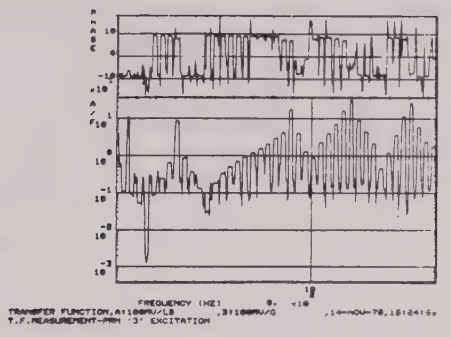


Figure 11. Measured Transfer Function PRN 3

The measured transfer function marked PRN 1 (Figure 9) corresponds to excitation by a pseudorandom noise sequence with a long interval between repetitions. This signal appears to be almost completely random since the interval between repetition is much longer than a block length of the FFT processor. The measured reponse labeled PRN 2 (Figure 10) excitation, corresponds to a shorter repetition interval in which several repetitions now occur within a block length. Although the measurement is still almost continuous, the finite steps in the measured and displayed frequency response function show that the excitation function now has finite spacing in the frequency domain rather than being continuous. Finally, the measured frequency response function labeled PRN 3 (Figure 11) excitation, corresponds to a highly repetitive pseudorandom noise waveform. Here, the high repetition rate of the pseudorandom sequence creates wider frequency spacing of the excitation waveform and the resulting transfer function measurement contains many "holes." Although this type of excitation can create a measurement which converges quite rapidly, it is clearly not always a desirable excitation function. However, if the characteristics of the pseudorandom sequence are optimized with respect to the processor being employed, several interesting phenomena occur which can be used to great advantage. This can be seen by examining the concept of excitation by a synchronous signal.

Synchronous Signal Generation (SSG)

In order to obtain the clearest representation of a measured frequency response function, it is necessary that each portion of the desired frequency range be sufficiently excited. Whereas the analog random signal previously investigated has many of the necessary qualities, it does require very specific processing such as windowing and averaging. Even though the variance of a transfer function measurement reduces much more rapidly than that of the input or output power spectrum when analog noise excitation is used, averaging and windowing is still almost always necessary. This is clearly seen in the two examples which show a real time display (Figure 12) of force and acceleration spectra using analog broadband excitation and a similar spectra after four blocks are averaged (Figure 13). In each case, even though spectrum peaks may be obvious, it is clear that additional smoothing is necessary.

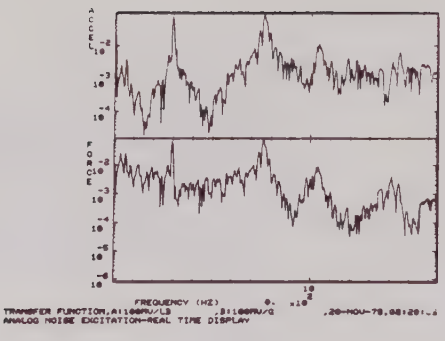


Figure 12. Force and Acceleration Spectra, Real Time

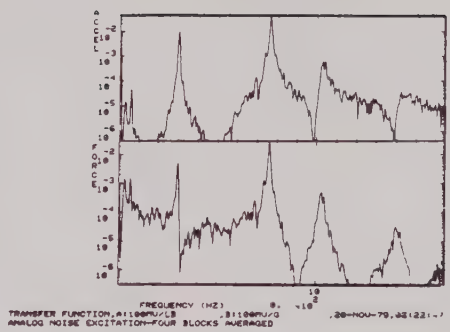


Figure 13. Force and Acceleration Spectral, Four Blocks Averaged

A very specific signal can be generated however which takes advantage of the characteristics of the FFT processor being used to measure the frequency response function. For example, if a 400 line FFT process is to be calculated based on a 1024 point Fourier transform computation, it is possible to generate a signal which is the equivalent of 400 equal amplitude sinusoids. Furthermore, the signal can be clocked and generated in such a way that each of the sine waves precisely lines up with a bin in the computed FFT process. If the phase of each of the equal amplitude sinusoids is randomly mixed, a signal is achieved which appears random in nature, but which repeats at precisely known periodic intervals. Furthermore, if the signal is generated at the same clock rate as the analog-to-digital converter which samples the signal, the signal can be processed with a flat or unweighted characteristic. This creates the narrowest possible processing filter, since truncation and leakage will not be a problem, giving optimum signal-to-noise enhancement and measurement dynamic range. An example of this type waveform with its resulting spectrum amplitude is seen in Figures 14 and 15. Note, the extremely flat spectrum content of the signal as analyzed using an unweighted processing characteristic.

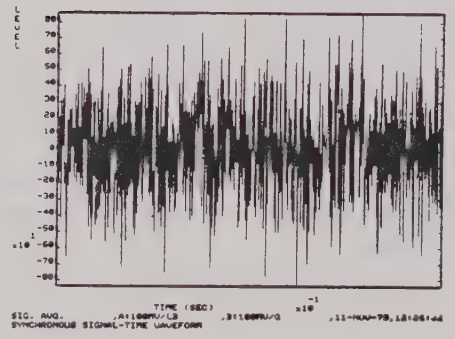


Figure 14. Synchronous Signal Generation Drive Waveform, 1 Sec Period

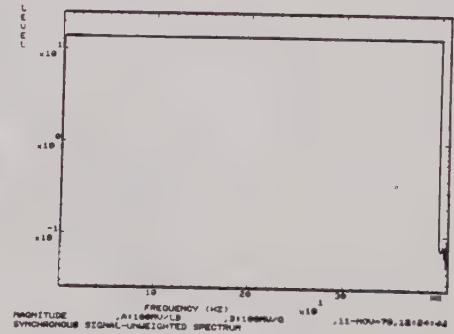


Figure 15. Synchronous Signal Generation Drive Signal

Using this signal to excite the same lightly damped structure as examined previously (Figure 16), a selected measurement can be made to converge quite rapidly. Figures 16 and 17 show both the force and response spectra and frequency response function measured using the SSG type excitation with an unweighted real time measurement. Note, the complete lack of leakage and variance if a linear system is excited creating no frequency shift and not requiring the smoothing effect of random amplitude averaging. Through the use of just a few averages, as shown in Figure 18, the measured transfer function with SSG excitation can be improved even further. Using this type of signal as an excitation source for testing operating systems will be discussed later.

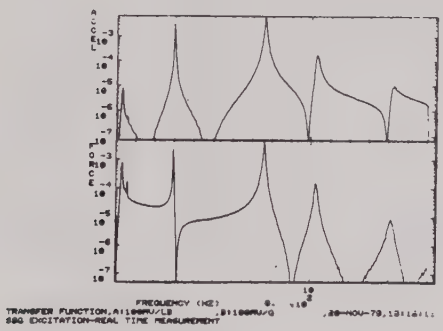


Figure 16. Force and Acceleration Spectra, SSG Excitation, Real Time

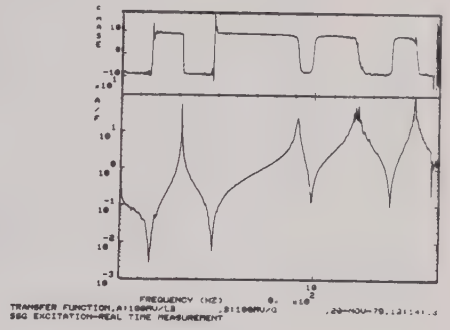


Figure 17. Transfer Function, SSG Excitation, Real Time

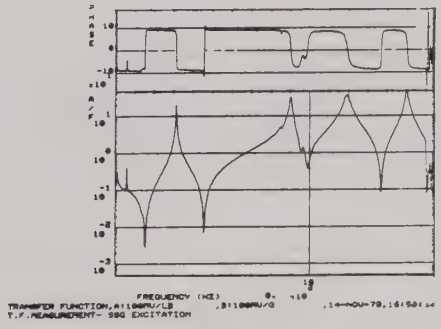
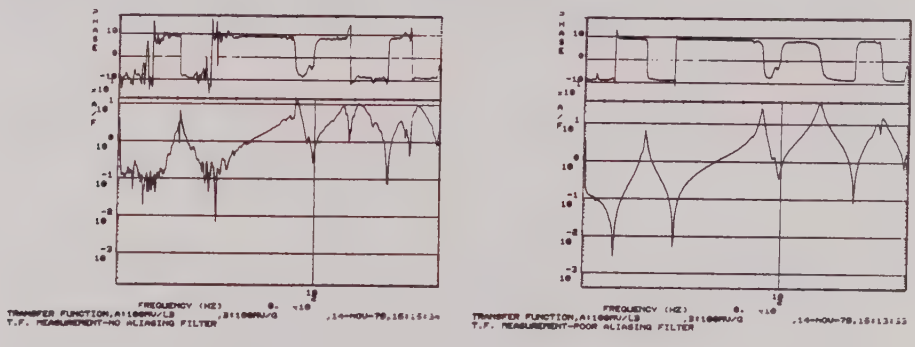


Figure 18. Transfer Function, SSG Excitation Averaged

Effects Of Poor Aliasing Filter

In virtually every type of analysis made using a digital sampling approach, some type of low pass or aliasing filter will precede an analog-to-digital conversion stage. The errors introduced into an analysis by not having a sufficiently sharp, or well-placed low pass aliasing filter will vary with the exact type of data being measured. In the previous example, a very lightly damped structure, the effects can be quite severe. The following example shows the results of two analyses

supposedly identical to the previous transfer function measurement, but actually with two different effects of poor aliasing filter protection, based on a variable filter cutoff characteristic. In Figure 19, note the effect the low pass aliasing filter has on the higher frequency mode. Obviously, it is not possible to draw a general conclusion about the effects of aliasing terms contributing to an otherwise correct measurement especially when transfer function measurements are involved. Nevertheless, it is extremely important to ensure that adequate aliasing protection is employed in each measurement, since aliasing terms cannot be removed once they become part of an otherwise valid measurement.



(a) *(b)*

Figure 19. Effect of Low Pass Aliasing Filter

WEIGHTING FUNCTION EFFECTS

In using a continuous shaker excitation signal, especially sinusoidal excitation, some type of symmetrical windowing function should be used to lessen or eliminate truncation effects due to finite block processing. If an improper window function is used, processed results will be in error. A correct windowing function not only reduces leakage errors, but also can contribute substantially to smooth convergence of the transfer function measurement. In Figure 20, the same transform processed previously is shown for a rectangular (unweighted) window. Note, the large truncation and bias errors which render this particular transfer function measurement almost meaningless. The proper use of various windows is explained clearly in an available technical paper on FFT Theory[1].

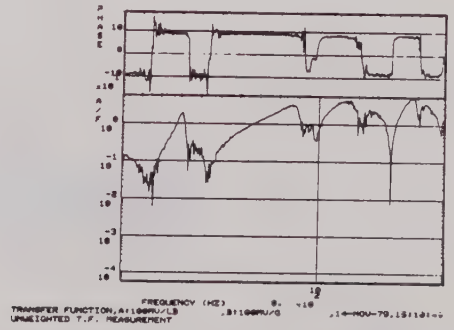


Figure 20. Unweighted Transfer Function Measurement

TIME AVERAGING

Coherent time averaging of complex waveforms, although not new, has only recently been employed on a large scale. Signal averaging can be done in the time domain only or the time average can be Fourier transformed. The three types of synchronous signal processing are:

- Synchronous averaging of operating data — to recover periodicities.
- Synchronous signal generation — to create a waveform suitable for broadband system excitation.
- Synchronous transfer function measurements — to recover system broadband characteristics in the presence of operating data.

Synchronous Time Averaging

Synchronous time averaging, which is mathematically related to cross-correlation analysis, is a technique to recover from a complex waveform only those periodic components which have a "phase-locked', or synchronous relationship with a reference periodic pulse. If several machines are operating in close proximity with each contributing to an overall noise or vibration level, a tachometer signal taken from one machine can be used to isolate the periodic contributions of that machine from an overall level measurement. Not only can noise contributions of individual machines be isolated, but contributions from individual sections of the machine can be isolated. For example, a twin spool turbine with a tachometer signal from each spool is operating. A signal from the tachometer on spool one or spool two can effectively be used to isolate the contributions from just that section of the turbine. Signal averaging techniques have been used to isolate propeller characteristics from other broadband noise contributions,[2] in wind tunnel measurements and to eliminate structural resonances from synchronous machinery operating data.

The concept of signal averaging is shown in Figure 21. A synchronous pulse, usually a 1/rev component in machinery analysis, is applied to the signal analyzer in conjunction with a composite noise or vibration signal. Figures 22 and 23 show a composite vibration signal measured on a bearing housing and the time averaged waveform recovered by synchronously averaging 256 frames of data with respect to a 1/rev fiberoptic tachometer signal. Note, the clearly periodic nature of the recovered waveform, with the complex components resulting from higher harmonics present in the vibration waveform in addition to the fundamental or running speed component.

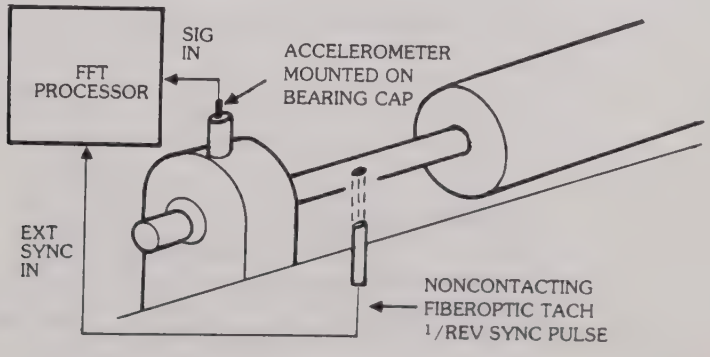


Figure 21. Concept of Signal Averaging

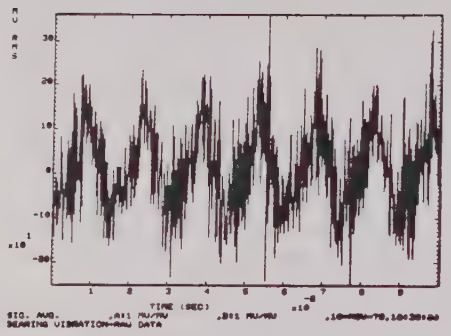


Figure 22. Operating Data, Acceleration Response at Bearing, 4080 rpm

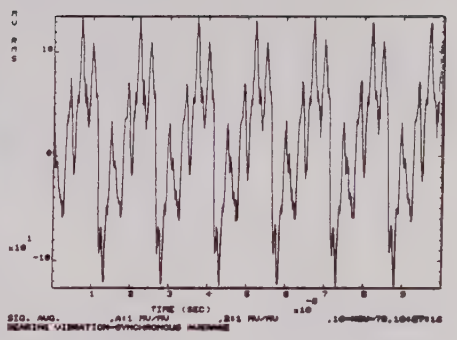


Figure 23. Synchronous Time Waveform, Bearing Acceleration, 4080 rpm, 256 Averages

Synchronous Spectrum Analysis

If the synchronous, time-averaging operation is followed by a single Fourier transform, the resulting spectrum is the synchronous spectrum. If sufficient averaging is performed in the time domain prior to the Fourier transformation, the synchronous spectrum will contain only periodic, harmonically related components. Figure 24 shows the normal composite spectrum from monitoring acceleration on a bearing housing near a second operating machine. The largest component in the entire spectrum occurs at 74 Hz and the measurement includes a significant amount of lower level broadband noise. When the same measurement is performed using synchronous averaging with respect to the 1/rev tachometer associated with the bearing being monitored, a remarkably clean operating spectrum results (Figure 25). Note that the highest level is now the 68 Hz component, whereas, the 74 Hz term and the broadband noise characteristics have been completely eliminated. Since normal spectrum averaging is performed on a power basis, it is important to realize that in synchronous spectrum measurements, no spectrum averaging is permitted. Coherent time-domain averaging must be followed by a single Fourier transform. If any spectrum averaging is performed during this operation, the power in nonsynchronous terms will contribute significantly and erroneously to the results.

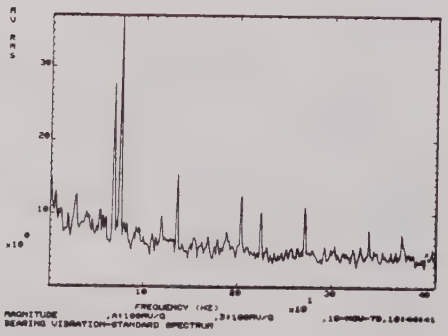


Figure 24. Standard Spectrum, 64 Averages

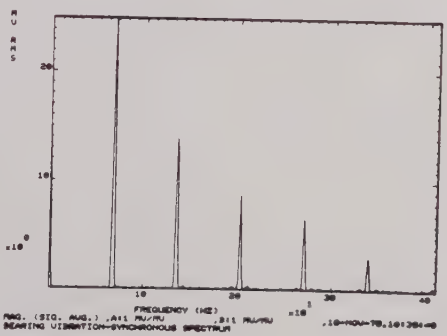


Figure 25. Synchronous Operating Spectrum

The important characteristics of signal averaging to recover periodic components can be summarized as follows (Figure 26).

SYNCHRONOUS TIME WAVEFORM

- A result of signal averaging
- Requires external periodic synchronous pulse
- Can only result in period waveform

$$\tilde{\tilde{S}}_X(\tau) = \frac{1}{T_1}\int_{-T_{1/2}}^{T_{1/2}} [S_X(t) + n(t)]\,\delta(t + \tau - nt_0)\,dt$$

- S/N improves with averaging time

SYNCHRONOUS SPECTRUM

- The Fourier Transform of a Synchronous Time waveform
- Requires external periodic Synchronous pulse
- Results in a periodic spectrum only — Lin or Log amplitude
- Single Fourier Transform only — *no spectrum averaging*

$$\tilde{\tilde{S}}_X(jw) = \{\tilde{\tilde{S}}_X(\tau)\}$$

Application — S/N improvements; enhance periodic data

Figure 26. Characteristics of Signal Averaging

Synchronous Signal Generation

The important characteristics of a synchronous signal were described earlier. This signal, used for broadband excitation when no other interfering or operating signals are expected, provides a series of spectrum components which are perfectly periodic in the window with respect to the FFT processor. This signal can often be used for rapid convergence of frequency response measurements. Its key characteristics can be summarized as follows (Figure 27).

SYNCHRONOUS SIGNAL GENERATION (SSG)

- A repetitive excitation signal which is always periodic "in the window" of a specified FFT processor.
- A signal which simulates N (e.g. 400 or 512) equal amplitude sinusoids
- Sinusoids summed with randomly mixed phase
- Excellent stimulation for linear system studies
- Can be processed with rectangular weighting for optimum S/N with minimum leakage
- Causes broadband TF measurements to converge in single pass

Figure 27. Characteristics of Synchronous Signal

Synchronous signal generation is discussed in depth in an available application note[3].

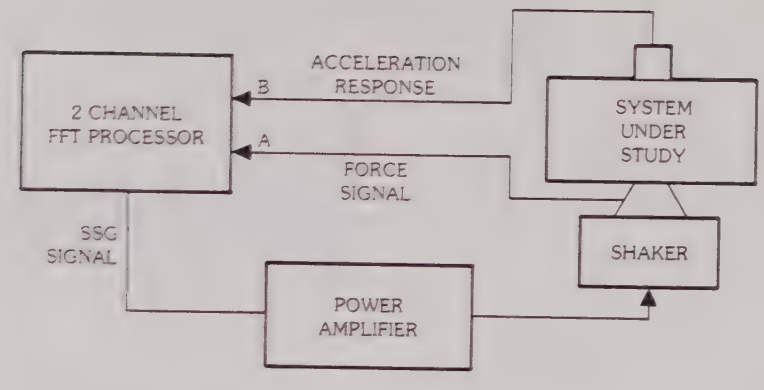


Figure 28. Use of SSG to Excite System

Synchronous Transfer Function Measurements

The synchronous spectrum measurements described previously represent an excellent means for enhancing periodic components and eliminating nonsynchronous or random events from the output of an operating system. In order to determine the frequency response of an operating system, the self-generating characteristics of the system must be eliminated, not enhanced. The frequency response function is a broadband characteristic; therefore, a broadband type of excitation must be employed. To eliminate unwanted periodic components, the measurement should be synchronized with the broadband excitation in much the same way that synchronous averaging was previously performed. In order to do this, the excitation signal must have a broadband characteristic with components at virtually every frequency, and it must be possible to synchronize to the signal by using a repetitive excitation source. Pseudorandom noise meets each of these requirements. The concept which will be employed in order to synchronize a measure of both excitation and response to the broadband source is given in the block diagram (Figure 29).

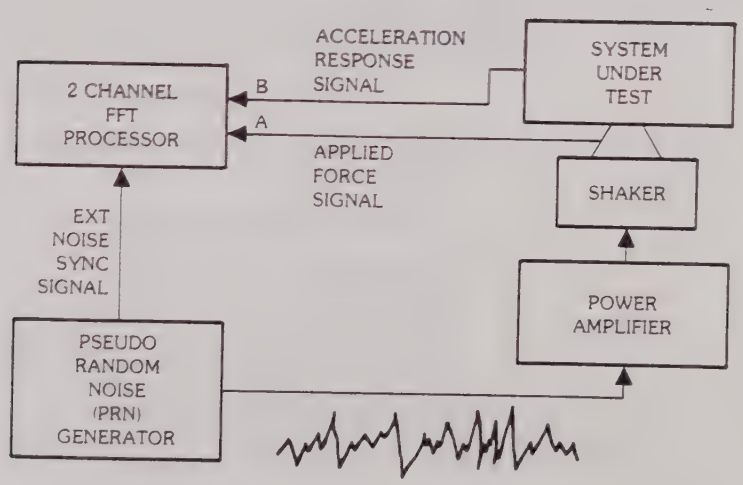
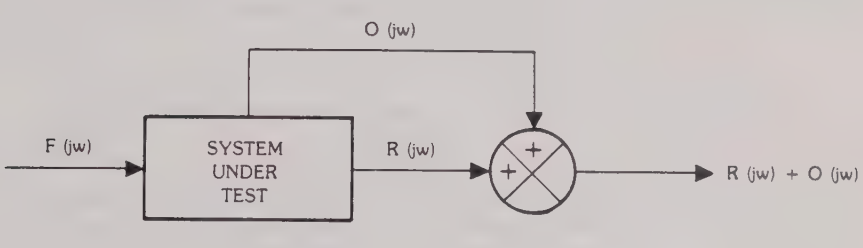


Figure 29. Concept of Synchronous Transfer Function Measurements

ANALYZING THE OPERATING SYSTEM

The general case of analyzing an operating system is seen in Figure 30. In the present example, the object of the measurement is to obtain the driving point accelerance transfer function on the bearing housing while the shaft within the bearing is rotating at approximately 655 rpm. First, the same driving point transfer function will be examined with the machine shut down. Six resonances can be seen between 20 Hz and 400 Hz (Figure 31). Also shown in Figure 31 are the driving point force and acceleration spectra during the broadband excitation. Note, that with the exception of one or two peak areas, the force spectrum is quite flat. The coherence function between acceleration and force indicates that a fairly high quality measurement has been made (Figures 32 and 33).



F (jw) = External system **forcing** function

R (jw) = **Response** of system to external forcing input

O (jw) = System **operating** characteristic added to forced response

X (jw) = Total measured forcing function

Y (jw) = Total measured system response

Figure 30. Analyzing an Operating System

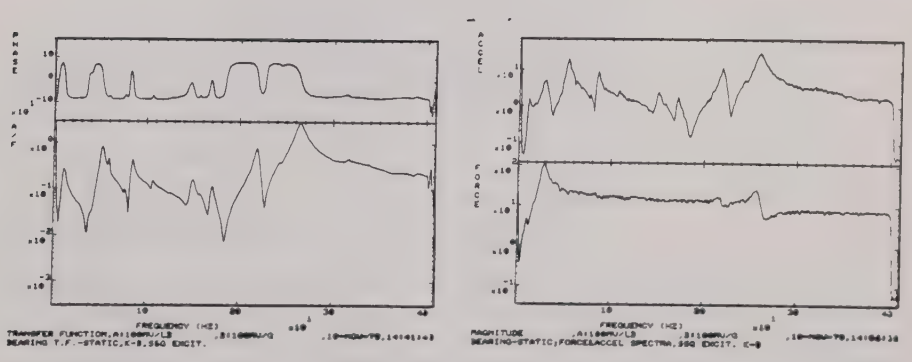


Figure 31. Transfer Function, Nonoperating Machine

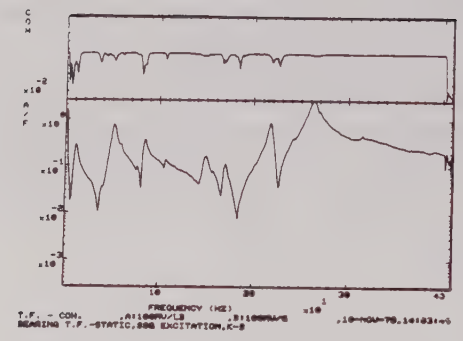


Figure 32. Bearing Transfer Function with Coherence

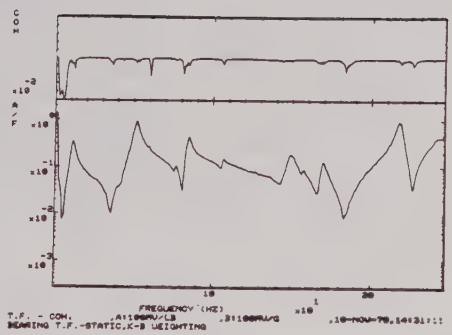


Figure 33. Zoom Display of Bearing Transfer Function with Coherence

When the same measurement is made with the system operating, note the drastic differences. Although similar force and acceleration spectrum shapes still exist, riding on top of this characteristic and almost completely masking the broadband excitation shape is the operating characteristic of the shaft/bearing combination and its periodic harmonics (Figure 34). The operating machine speed of approximately 655 rpm produces a dominant characteristic which a standard spectrum measurement shows clearly. If an attempt is made to perform a frequency response measurement based on the excited operating system with force and responce spectra as just seen, the results are very unsatisfactory. Figure 35 shows a frequency response measurement using a standard cross-spectrum/input power spectrum measurement technique. The frequency response function and coherence function (Figure 36) show irregular peaks at the harmonics of the operating system, clearly not representative of the true bearing frequency response function.

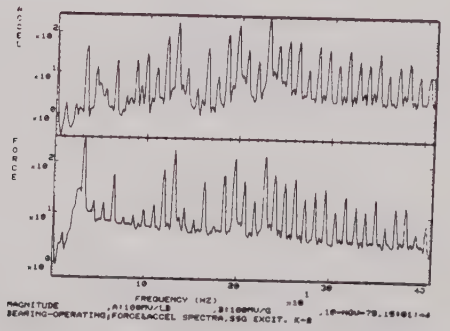


Figure 34. Force and Acceleration Spectra, Operating System

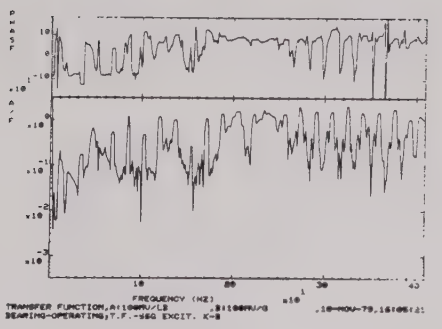


Figure 35. Frequency Response, Operating System

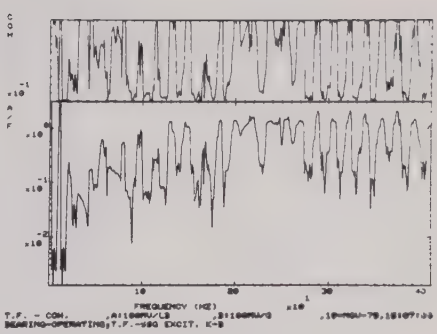


Figure 36. Coherence Function, Operating System

Characterizing Machine Signatures

Several techniques are currently in use for characterizing the signature of an operating machine system[4]. A technique which visually enhances the data is to to display the amplitude/frequency/time history of a machine system as it accelerates or decelerates using a 3-D display. The characteristic bearing signature for the machine under investigation is shown in Figure 37. As the running speed is increased from about 600 rpm to 3000 rpm, several frequencies of apparently higher response in the region of 210 Hz and 230 Hz are seen. The fact that these frequencies may represent system resonances is given credence by the corroborating peaks in the previously measured frequency response function seen in Figure 31. In the 3-dimensional spectrogram, note also the steady occurrence of the 120 Hz tone generated by the large motor used as a primary system power source.

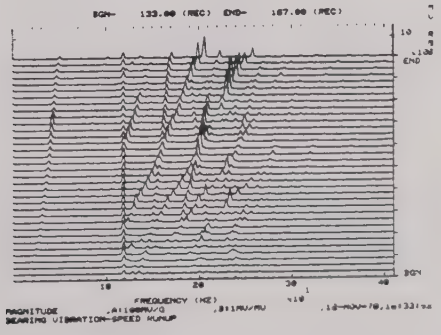


Figure 37. Bearing Signature, Operating System

Synchronizing Broadband Excitation of the Operating System

In order to eliminate the operating characteristics of the machine from the measured frequency response function, pseudorandom excitation will be employed and the response measurement synchronized to the excitation source. A frequency range of 400 Hz similar to the previous measurements was used. Force and acceleration spectra were calculated by performing a single Fourier transform after time averaging the force and acceleration time waveforms over 512 time records. The averaged pseudorandom noise time waveforms for both force and

acceleration are shown in Figure 38. Note that the one second averaged block length for these records corresponds to slightly more than one repetition interval of the pseudorandom noise sequence. The power spectra of each of the time-averaged records was calculated and is displayed in Figure 39. Since time averaging has been performed, the resulting signal to be processed is a single averaged block of acceleration and force. This means there can be no spectrum averaging.

Having eliminated the operating characteristics from the data through the use of synchronous averaging, it is then a straightforward matter to calculate the ratio of the Fourier transforms of the force and response waveforms. The results of calculating this synchronous transfer function for both rectangular and symmetrical Kaiser-Bessel windowing are seen in Figures 40 and 41. Note, the correspondence between these measurements and the measurements of Figure 31 for the nonoperating situation. Although parameters such as bearing stiffness might change for the operating case and may, in fact, represent desirable information, the correspondence between Figure 31 for the nonoperating case and Figures 40 and 41 for the operating situation is excellent. The use of the synchronous transfer function measurement approach can eliminate to a large extent

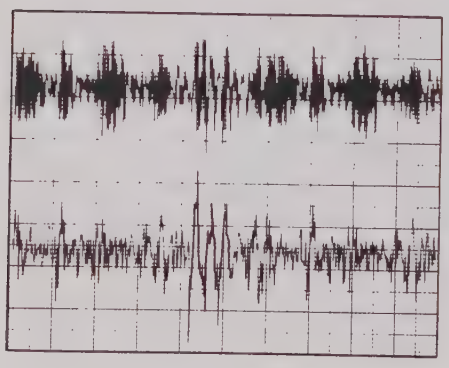


Figure 38. Noise Synchronous Waveforms, Acceleration and Force, 512 Averages

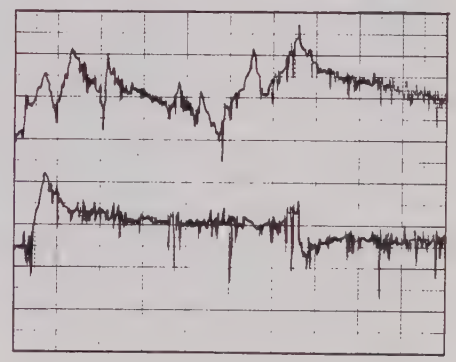


Figure 39. Force and Acceleration Synchronous Spectra, 512 Averages Operating System

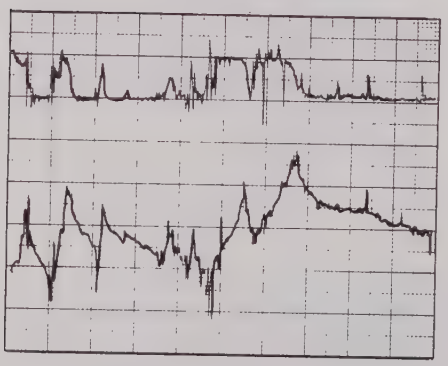


Figure 40. Frequency Response Function, Synchronous Measurement, Rectangular

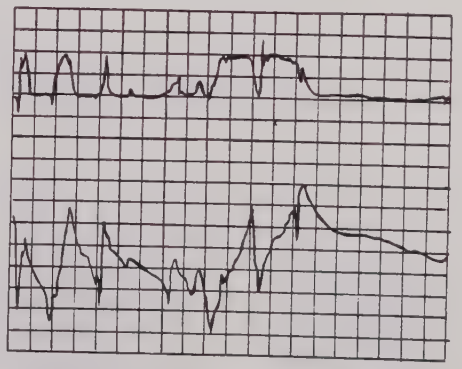


Figure 41. Frequency Response Function, Synchronous Measurement, KB Weighting

operating or driven system characteristics, thus, permitting broadband frequency response characteristics to be conveniently determined.

The key characteristics of synchronous transfer function measurements can be summarized as follows (Figure 42).

SYNCHRONOUS TRANSFER FUNCTION

- Ratio of Fourier Transforms of two time averaged signals
- Time averaging followed by single Fourier Transform
- Requires external stimulus of system under study
- Broadband stimulus usually of Pseudo Random Noise (PRN) with noise Synchronous

$$\tilde{\tilde{H}}_{YX}(jw) = \frac{\tilde{\tilde{S}}_{Y}(jw)}{\tilde{\tilde{S}}_{X}(jw)}$$

Application — remove periodic signals; enhance externally excited frequency response functions of operating systems

Figure 42. Key Characteristics of Synchronous Transfer Function Measurements

SUMMARY

With an operating system, the total measured response may contain a contribution from both the internal operating characteristics and possibly from external forces acting on the system. An example could be a response measurement made on machine #1 which contained the operating characteristics of machine #1 plus some forced vibration from machine #2 operating nearby. It was shown that the characteristics of machine #1 can be enhanced to the exclusion of all other signal characteristics through the use of synchronous time averaging and the synchronous spectrum. To perform this operation, only a transducer signal from the appropriate machine is required and a unique tachometer signal capable of isolating the once per revolution characteristic of the machine being studied.

For the nonoperating case, in order to establish a broadband frequency response characteristic, such as bearing stiffness, it is necessary to provide a suitable broadband system excitation. Several types of system excitation were investigated, including pseudorandom noise and synchronous signals. For the nonoperating system virtually any type of broadband excitation is sufficient to allow measurement of the desired frequency response characteristic. However, in the presence of operating system characteristics, normal frequency response measurement techniques are unable to produce the required results.

To measure frequency response functions while a system is in operation, it is necessary to combine coherent time-averaging techniques with a special type of excitation signal. By combining two channels of signal averaging with a frequency response function ratio measurement, operating system characteristics can be removed, revealing true broadband frequency response characteristics. These measurements are now possible using commercially available analysis instrumentation.

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2. Pierson, A.G.; Wilby, E.G.; and Wilby, J.F., "Evaluation of Aero Commander Propeller Acoustic Data: Taxi Operations. NASA Contractor Report 159124.

3. Keller, A.C.; Synchronous Signal Generation (DSP-021); Spectral Dynamics, Scientific-Atlanta.

4. Keller, A.C.; Spectrum Analysis in Machinery Health Monitoring, (DSP-030); Spectral Dynamics, Scientific-Atlanta.

APPENDIX A

TRANSFER FUNCTION PEAK INVERSION

The accuracy of frequency response function measurements made using an FFT approach is dependent upon the resolution of the FFT process employed. This is particularly true for structural measurements on lightly damped systems. The accuracy of damping and peak response measurements is directly related to the number of measurement points within either 3 or 6 dB of the measured frequency response peak. To achieve a measurement accuracy of 2%, at least six measurements points must be present within the 3 dB bandwidth of the measured structural peak response. For measurements made on lightly damped systems, even with 500 lines across a baseband measurements frequency range, only 1 or 2 measurement points may exist within the frequency range of a high Q peak. An even more severe measurement problem can exist if the bandwidth of a high Q resonant peak is actually narrower than the filter spacing of the FFT processor performing the measurement.

Figure A-1 shows a driving point transfer function measurement determined using analog random noise excitation. This measurement covers a 2 kHz range and was made with 4 Hz resolution. One of the frequencies of interest, which appears as an apparent resonance, is near 300 Hz. At this frequency a double peak is seen even though only a single phase shift indicating a single resonance is indicated. The coherence however gives an extremely low indicated value, approximately 0.03 (Figure A-2). In the expanded display of Figure A-3 the region from

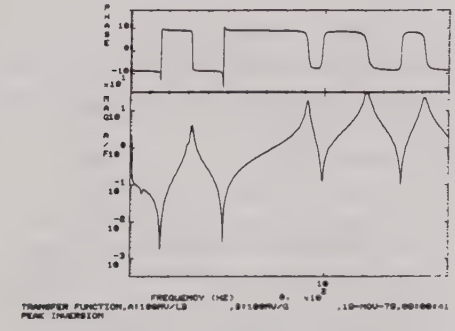

Figure A-1. Transfer Function, Random Noise Excitation

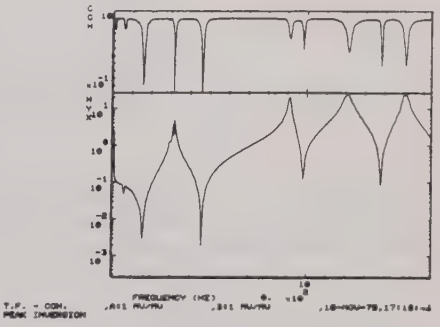

Figure A-2. Coherence Function

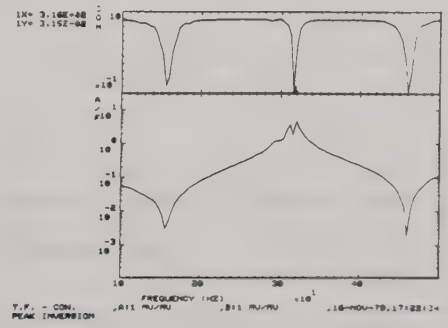

Figure A-3. Zoom Display of Transfer Function

100 Hz to 500 Hz is shown and the coherence function corresponding to the frequency response "dip" labeled as position 1. What causes this transfer function "dip"?

Examine the transmissibility between acceleration and force and the peak inversion does not occur. This is seen in both the broadband and expanded displays of Figures A-4 and A-5. The transmissibility function is the square root of the ratio of the response acceleration to the driving force. Figure A-6 shows a broadband display of the force and acceleration spectra during this transfer function measurement. An expanded display of these two spectra shows that the peak in the force spectrum occurs at 297 Hz (Figure A-7). This, however, is not the resonant frequency. The true resonance occurs at the force minimum which occurs at approximately 316 Hz. Thus, an important characteristic contributing to the "peak inversion" phenomena is that it occurs when the denominator of the transfer function measurement equation (the power spectrum of the applied force) is at a minimum or attempts to go to zero.

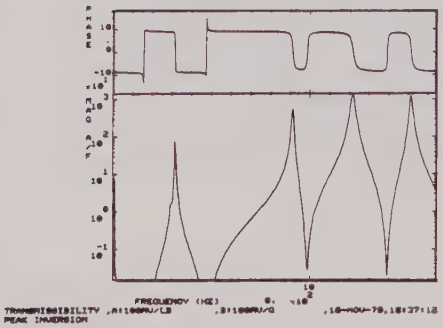

Figure A-4. Transmissibility

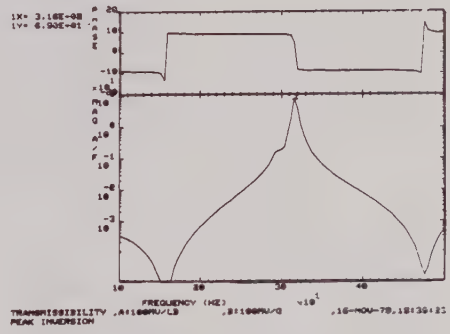

Figure A-5. Transmissibility Zoom Display

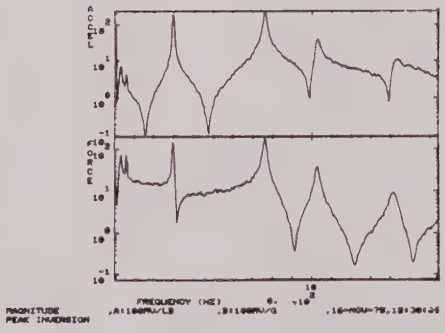

Figure A-6. Force and Acceleration

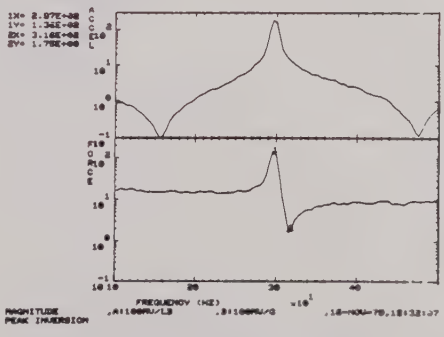

Figure A-7. Force and Acceleration Zoom Display

This is even more readily apparent by observing the cross-spectrum between acceleration and force. Keep in mind that this quantity is the numerator in the computation used to determine the frequency response function. Figure A-8 shows a broadband look at the cross-spectrum used in this computation. Note, that the peak of the cross-spectrum occurs at 297 Hz which also corresponds to the peak in the force spectrum. However, a very sharp notch in the cross-spectrum occurs at approximately 315 Hz corresponding also to the correct phase shift (approximately 90 degrees) necessary for a true resonance indication. An expansion of the cross-spectrum display shows the notch in the cross-spectrum at the resonant frequency of approximately 317 Hz (Figure A-9). Thus, the broadband measurement being made on the frequency response function involves a resonant frequency measurement in which a "dip" in the cross-spectrum is to be divided by an even greater "dip" in the input power spectrum.

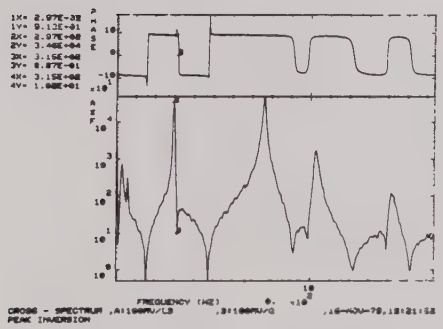

Figure A-8. Cross-Spectrum

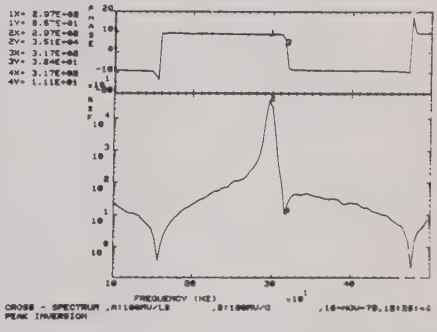

Figure A-9. Cross-Spectrum Zoom Display

Another of the key characteristics which adds to this "peak inversion" phenomena is the use of a symmetrical windowing function during the FFT processing. As described previously, the peak inversion problem becomes of concern primarily when the resonant bandwidth of the system being excited is actually less than the spacing of the FFT bins created during the signal processing procedure. In a symmetrical weighting function such as the Hanning or Kaiser Bessel window, the effective filter shape of the FFT process is precisely defined by the window itself. For example, in the Kaiser-Bessel window if the peak of the filter created by the window is set at 0 dB, the adjacent points on the filter shape are automatically down 4.1 dB. Thus, if a narrowband resonance is indicated as a peak narrower than the FFT spacing, it can appear to the processor as a periodic signal and the resulting side lobes will assume the shape of the weighting function rather than the true peak situation which is much less lightly damped. Note, that the effective filter shape created by the window function is a factor in the measurement both during peak and notch phenomena in the spectra. Figure A-10 shows the situation if a rectangular window is employed and the transfer function resonant peak occurs right at the center of an FFT bin. In this case, the denominator (input power spectrum) is left free to experience the deep notch compatible with the input signal characteristics. Even though the cross-spectrum has also experienced a notch at this frequency, for the unweighted example the deeper notch of the input power spectrum creates a ratio which results in an extremely high transfer function peak.

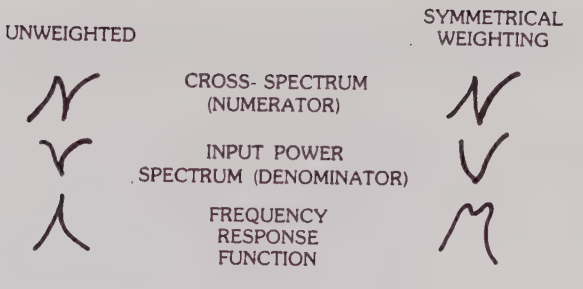

Figure A-10. Peak Inversion Problem Shown with Very Low Driving Force and Symmetrical Weighting Function

If the same situation is examined in conjunction with a symmetrical weighting function such as the Kaiser-Bessel window, neither the cross-spectrum "dip" nor the input power spectrum "dip" are permitted to achieve the full depth of their notch. The result is that instead of a sharp peak in the resulting frequency response function, the center or peak value is pulled down by the shape of the weighting function. An additional factor contributes to transfer function "peak inversion" is the dynamic toggling of the least significant bit in the processor which is computing both the cross-spectrum and the input power spectrum. Since one complete shift of the least significant bit in either the numerator or denominator may cause a 6 dB variation in calculated transfer function amplitude, it is easy to see that an average error of between 3 dB and 6 dB can be present in the computed frequency response ratio depending upon the number of bits available for the calculation and any processing tricks which may be employed, such as dithering of the one or two least significant bits in the computation. Note, that if the two least significant bits in the denominator are processed with a random dither signal, a 6 dB difference can occur between the true frequency response function peak and the apparent peak with foldover. What is the solution to this apparent dilemma? Obviously, the resolution of the FFT analysis must be made equal to or less than the bandwidth of the resonance being measured.

Increased resolution can be achieved through the use of zoom techniques. In the zoom transform approach, the full measurement resolution of the processor is concentrated into a selected narrow region of the spectrum. In the current example, the zoom factor of 10 was employed increasing the FFT resolution from 1 Hz to 0.1 Hz. The results of this improved resolution are seen in Figures A-11 and A-12. Note, that with the improved resolution, the phase across the resonant

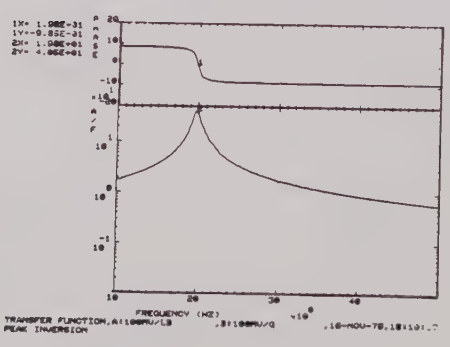

Figure A-11. Transfer Function Zoom Display

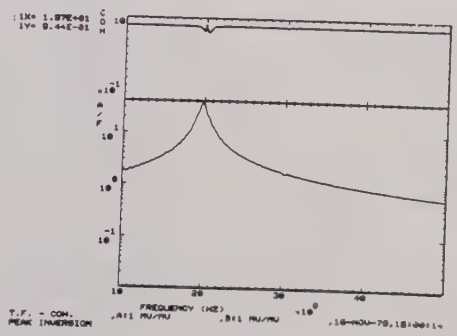

Figure A-12. Coherence Function Zoom Display

peak is now defined with 12 sample points; whereas previously, the entire 180 degree phase shift occurred within approximately one cell. Perhaps even more importantly, the coherence function shows a dramatic improvement from less than 0.05 to greater than 0.94. Note, that in the zoom measurement, nothing physically is changed on the structure or with the vibration exciter. The only change that occurs is in measurement resolution. Other excitation techniques can sometimes be employed to improve apparent measurement resolution and reduce or eliminate peak inversion effects. However, in general, the use of zoom techniques will consistently eliminate any foldover effects in the measured frequency response function.

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